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KEVLAR PROPERTIES INVESTIGATION
HIGH SPEED ABRASION RESISTANCE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Kevlar has acquired a reputation for poor abrasion resistance. Replacement of nylon parachute materials with Kevlar has been hampered by Kevlar's reputation. However, abrasion testing of these materials under conditions designed to simulate parachute deployment had never been performed.

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20. ABSTRACT (cont.)

A test procedure was designed to simulate the high speed rubbing of Kevlar and nylon webbings, braids and ribbons against themselves and a common abrasive surface under various conditions of loading at speeds ranging from 20 to 240 fps. Evaluation of abrasive damage was based upon strength loss for each material at each test condition.

Extensive testing of both Kevlar and nylon materials showed conclusively that Kevlar's resistance to abrasive damage sustained due to high speed rubbing was superior to that of nylon. Investigation of the effects of many test parameters on strength loss due to abrasive damage showed that Kevlar relative to nylon was much less affected by test speed and normal force due to its superior thermal stability.

FOREWORD

This report was prepared by FRL, A Division of Albany International Corporation, Dedham, Mass., under U. S. Government Contract No. F33615-78-C-3406. The work was initiated under Project 2402, and was conducted from February 13, 1978 through January 31, 1980. The contract was administered by the Air Force Flight Dynamics Laboratory, Air Force Systems Command, with Mr. W. R. Pinnell acting as Project Engineer.

Mr. Norman J. Abbott was the FRL Associate Director responsible for the overall program. The majority of equipment design was performed by Mr. Robert E. Sebring, Senior Research Associate at FRL. The laboratory studies were carried out by Mr. Stephen L. Goodwin and Mr. James F. Geib. For many helpful discussions throughout the course of the work, the authors wish to express their appreciation to Dr. John Skelton, Associate Director at FRL, and Dr. Milton M. Platt, Director at FRL, who also handled contractual matters.

This report was submitted by the authors in January 1980.

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Code for Figures Showing Strength Loss Due to Abrasion

Width/Strength/Abraded Material - Test Configuration - Abrading Material

1/6,000/K || K — 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration

K - Kevlar
N - Nylon
A - Abrasive

|| - Parallel Test Configuration

$\perp$ - Perpendicular Test Configuration

T - Obvious Thermal Effects (Scorching, Melting, Glazing)

LIST OF TABLES

SECTION I

INTRODUCTION

Kevlar 29 woven narrow fabrics and braided cords have been replacing nylon in many decelerator systems. The use of this new high modulus material has raised many questions about its performance and mechanical properties. One major area of concern has been the abrasion resistance of Kevlar. Nylon is generally recognized as having excellent abrasion resistance for a fibrous material. Kevlar has acquired a reputation for poor abrasion resistance. Some parachute designers and engineers faced with selecting materials for use in decelerator systems have hesitated in selecting Kevlar over the widely used nylon materials. These people feel that Kevlar's high strength to weight ratio cannot be utilized advantageously if the material cannot withstand the conditions of high speed deployment without significant strength loss due to abrasion. Also, in applications where repeated use is a design requirement, the durability of Kevlar remains somewhat in question.

Kevlar's reputation for poor abrasion resistance has come mainly as a result of abrasion tests performed on the so-called "hex bar" abrader which was developed for evaluating nylon webbing and is described in MIL-W-4088. This information is included in Air Force reports concerning the properties of Kevlar investigated in the early stages of Kevlar development[1]. These reports showed that Kevlar sustained extremely high strength losses in comparison with nylon materials abraded under similar conditions. This test apparatus and procedure did not simulate actual conditions of decelerator systems deployment or operation. The testing was performed at a very low speed and normal force and the abrasion resulted from rubbing over sharp metal edges. Clearly this test method did not simulate decelerator systems conditions. Another indication of Kevlar's poor abrasion resistance had come from comments made by persons associated with the actual weaving of Kevlar structures. Kevlar weaving had proven to be a difficult task due to its low elongation which often resulted in length differentials in the warp. Winding, twisting, and weaving of Kevlar yarns often left substantial quantities of broken Kevlar fibers on metallic parts which guided the yarns through the processes. Warp yarns removed from woven structures often showed lower tensile strength than yarns taken directly from the package. Here again, however, this information said nothing about the abrasion resistance of woven structures, especially under decelerator systems conditions.

The purpose of this work was therefore to simulate the conditions associated with decelerator systems deployment and operation. Both Kevlar and nylon materials were to be abraded at high speeds under various conditions. Although actual simulation of these conditions is an impossible task, it was hoped that a good comparison of abrasion resistance between Kevlar and nylon could be made under conditions more closely approximating end use conditions than the hex bar abrader.

SECTION II

DESCRIPTION OF PROGRAM

A. Program Requirements

Two forms of abrasion were to be investigated in this program. These were Kevlar on Kevlar (or nylon on nylon) and Kevlar (nylon) on abrasive surface with a surface roughness approximating that of a concrete runway. Two test configurations were to be used. These were parallel axis contact (longitudinal axis of both specimens parallel) and normal axis contact (longitudinal axis of one specimen perpendicular to that of the other). For the Kevlar on Kevlar abrasion, both specimens were to be tensioned, one specimen tensioned to 25% of its rated strength in the parallel configuration. Minimum length of contact between the abraded specimen and the abrading surface was to be one foot for the webbings and braids and 6 inches for the ribbons and tapes in the parallel abrasion configuration. Abrasion of Kevlar on Kevlar in the perpendicular configuration required that the abrading specimen have a minimum length of rubbing of 8 feet. Relative velocity requirements called for investigation of abrasion effects at 3 velocities between 50 and 250 fps and one velocity below 50 fps for the Kevlar on Kevlar abrasion. Abrasion on simulated concrete was to be investigated at 3 velocities between 30 and 200 fps and one velocity below 30 fps for all materials.

At each velocity, abrasion effects were to be investigated for at least 4 degrees of abrasion. In the Kevlar on Kevlar (nylon on nylon) abrasion, both the abraded and abrading specimens were to be evaluated for effects of abrasion. Evaluation of abrasion effects was to be based on change in weight per unit length, change in thickness, and residual tensile strength for both the abraded and abrading specimens. Evaluation of residual tensile strength was to be based on a data base value generated using test methods developed for Kevlar in the first phase of this program[2]. This data base value was to be derived from a minimum of 20 tensile tests. At the conclusion of the program, a comparison was to be made between similar Kevlar and nylon structures in order to determine the relative abrasion properties.

During the course of the work, it was found to be impractical or impossible to comply with all of these requirements for all of the materials. Reasons for modifications in the test plan will be made clear in the body of the report where the testing is described and the results are discussed.

B. Materials

The materials involved in this program were to be supplied by the contractor and manufactured according to military specifications[5,6]. Construction details for the materials involved in the program are given in Table 1. The materials range in strength from 460 to 9,000 lbs and in width from 3/4 to 2 inches. Included in the group are a variety of constructions of webbings, ribbons, tapes and braided cords. Not all of the materials were to be tested in all configurations (see Table 2). In general, the lightweight materials were only to be tested on abrasive paper while the other materials were to be tested in all configurations with some exceptions. The 2 inch 500 lb Kevlar ribbon was originally to be coated before testing. However, the lack of a suitable coating prevented this.

TABLE 1

MATERIALS FOR ABRASION TESTING

Material Type and Specification	Nominal Tensile Strength (pounds)	Width (inch)	Weight (oz/yd)	WARP YARNS Total Ends	Denier	Ply	Twist per Inch	FILL YARNS Ends per Inch	Denier	Ply	Twist per Inch	Weave
Kevlar Webbing [5] Type IV, Class 1	500	3/4	0.10	90	200	1	2	38	200	1	0	Plain
Kevlar Webbing [5] Type VI, Class 9	6,000	1	1.00	44	1,500	3	2	10	1,500	1	0	Plain
Kevlar Webbing [5] Type VI, Class 10	9,000	1	1.50	76	1,500	3	2	8	1,500	3	0	2/2 HBT Center Reversal
Kevlar Webbing [5] Type X, Class 5	4,000	1-3/4	0.60	55	1,000	2	2	15	1,000	1	0	Plain*
Nylon Webbing MIL-W-27657 Type III	6,000	1	1.65	224	840	2	2-1/2	16	840	2	2-1/2	5/1 1/5 HBT Center Reversal
Kevlar Ribbon [5] Type V, Class 8	1,000	2	0.18	150	200	1	2	45	200	1	0	Plain
Kevlar Ribbon [5] Type V, Class 3	480	2	0.121	60	200	1	2	50	200	1	0	Plain
Nylon Tape MIL-T-5608E Class D, Type II	460	2	0.36	154	210	1	1	52	210	2	2-1/2	2/2 RH Twill
Nylon Tape MIL-T-5608E Class E, Type II	1,000	2	0.53	378	210	1	1	36	210	2	2-1/2	2/2 RH Twill
Kevlar Cord [6] Type IX	2,000	--	0.32	16	1,500	3	1	6.5				
Nylon Cord MIL-C-7515B Type VI	2,000	--	0.80	192	840	1	2-1/2	4.5-6.5				

*Not MIL Spec. weave.
[5,6] See references at end of report.

TABLE 2

ABRASION TESTING PLANNED FOR EACH MATERIAL

Material Type and Specification	Test Configuration: Kevlar on Kevlar		Kevlar on Abrasive Surface	
	Parallel	Perpendicular	Parallel	Perpendicular
Kevlar Webbing Type IV, Class 1	X	X		
Kevlar Webbing Type VI, Class 9	X	X	X	X
Kevlar Webbing Type VI, Class 10	X	X		
Kevlar Webbing Type X, Class 5			X	X
Nylon Webbing MIL-W-27657 Type III	X	X	X	X
Kevlar Ribbon Type V, Class 8			X	X
Kevlar Ribbon Type V, Class 3			X	X
Nylon Tape MIL-T-5608E Class D, Type II			X	X
Nylon Tape MIL-T-5608E Class E, Type II			X	X
Kevlar Cord Type IX	X	X	X	X
Nylon Cord MIL-C-7515B Type VI	X	X	X	X

SECTION III

TESTING EQUIPMENT AND PROCEDURES

A. Description of Test Apparatus

Figure 1 shows a schematic of the test apparatus used for high speed abrasion of these materials. Movement of the abrading specimen was attained through the use of a rotating wheel. The wheel was attached to the shaft of a 2 speed 10 hp 3 phase electric motor. Motor speeds were 1750 and 1160 rpm. Two steel wheels were fabricated. These had rim diameters of 32 and 16 inches respectively. Also, a second motor (1740 rpm, single speed, 3 phase, 2 hp) was mounted beside the larger motor. The smaller motor was coupled to the small wheel through the use of a timing belt and pulleys. Speed reductions of 3 to 1 and 6 to 1 were attained by changing timing pulleys on the small motor. In operation with the smaller motor, the larger motor was locked out and its shaft and bearings used for supporting the wheel as it was driven. This drive system resulted in 6 speeds which were 244, 162, 122, 81, 40 and 20 fps. These were obtained with the drive combinations listed in Table 3. Because of the energy stored in the spinning 32 inch diameter wheel, a pneumatically operated disc brake was installed between the wheel and the motor housing. This helped to speed up the testing by minimizing stopping time for the wheel at the completion of a test.

TABLE 3

EQUIPMENT COMBINATIONS GIVING VARIOUS OPERATING SPEEDS

Linear Surface Speed (fps)	Wheel Circumference (inches)	Rotational Speed (rpm)	Timing Pulley Reduction
244	32	1750	---
162	32	1160	---
122	16	1750	---
81	16	1160	---
	32*	1740	---
40	16	1740	3:1
20	16	1740	6:1

*This combination was only used for the work described in Section IX, page 110.

The wheels were fabricated from a steel hub, solid back plate and rim, all pieces welded. The wheel rims were 4 inches wide with a 2 inch flat in the center of the rim and a 1 inch x 3/16 inch chamfer on either side of the flat. A 2 inch x 2 inch square cut-out (slot) was made in the flat on each rim and the edges of the slot were radiused to avoid cutting of the sample. Both wheels were statically balanced in order to minimize vibration. The abrading sample was wrapped around the wheel rim and positioned on the flat. The ends of the specimen were passed through the slot and held in place by two pin clamps. These two pin clamps were positioned equidistant from the rotational axis of the wheel and motor, 180^{o} opposed (Figure 1). Slots were

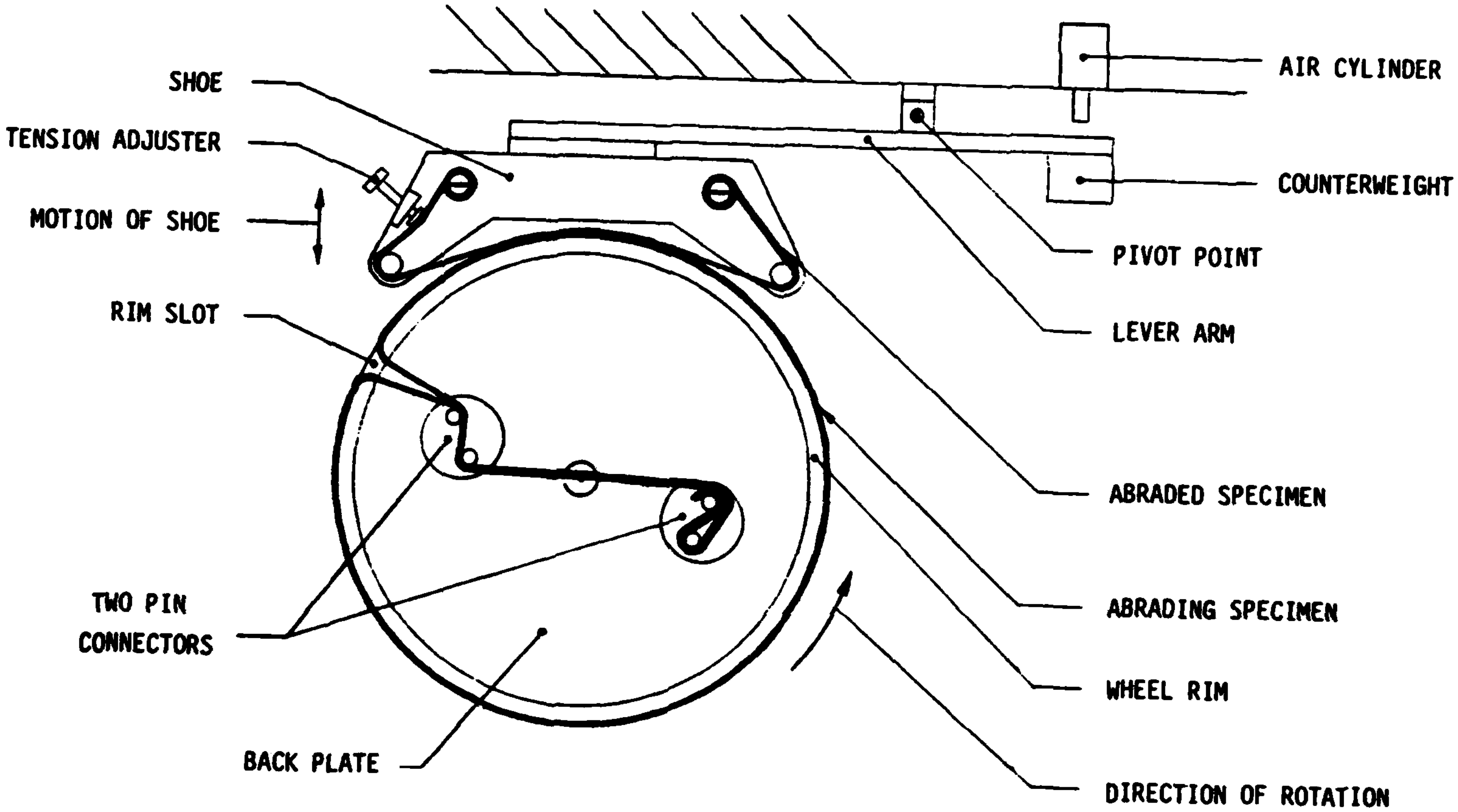


Figure 1. Schematic of High Speed Abrasion Apparatus

milled in the two pin connectors which allowed it to be bolted (4 bolts) to the wheel back plate in any rotational position. This design allowed for near perfect balance and vibration was not a major problem. For the perpendicular configuration, a PVC block was bolted to the back plate at the rim slot. This effectively shortened the slot (as the fabric was wrapped over the block) which avoided cutting of the abraded specimen on the edges of the slot during testing.

The abraded specimen was clamped to a fixture similar to a brake shoe in operation. Figure 1 again shows the configuration. The abraded specimen was passed around two fixed pins, one on either end of the brake shoe as shown. The ends of the specimen then passed back toward the top center of the shoe to the slotted clamping pins. The ends then passed through the slots and the pins rotated to take up excess slack in the material. Set screws were used to hold the pins after sample installation. A fine tension adjustment was installed in one end of the shoe. Adjustment of specimen tension was provided through the use of a threaded rod and radiused foot which produced a lateral deflection of the specimen between the fixed and rotating pins on one end of the shoe. The shoe arrangement was then bolted to a pivoting lever arm made from an aluminum plate. The bolt pattern allowed for fastening of the shoe to the lever so that the longitudinal axis of the abraded specimen was either parallel or perpendicular to the direction of wheel rotation (and abrading specimen motion). This allowed for testing in the two configurations (parallel and perpendicular). The shoe was weighted to attain a maximum contact force and a segmented counter weight system was hung from the opposite end of the lever arm. This allowed adjustment of the contact force by removal of weights. An air cylinder and rod were attached to the frame of the machine and raised the shoe by application of a force on the counterweight end of the lever. A bubble level was attached to the upper side of the lever in order to set the lever to a level position at the start of the test.

The whole assembly was made rigid through the use of welded steel channel frame. For maximum safety, the apparatus was bolted to the floor in an isolated room. A Lexan window was installed in the wall and operational controls mounted outside of the room. This apparatus proved to be safe and trouble free throughout the program. Figures 2 and 3 are photographs of the test apparatus in the parallel and perpendicular test configurations respectively.

B. <u>Adjustment of Test Apparatus</u>

Before the start of each test series, the apparatus was checked and adjusted to suit the particular material and configuration of the test. The shoe was centered vertically above the motor shaft so that the center of the free length between contact pins contacted the highest point on the wheel. This assured balance of the vertical components of the frictional forces. This was especially important in the parallel test configuration. It was also necessary to center the shoe over the center of the flat on the wheel rim (along the center line of the motor shaft). This assured deflection at the center of the length between contact pins and even pressure distribution in the perpendicular test configuration. At the same time, the center line of the lever had to be parallel to and centered over the circumferential center line of the flat of the wheel rim. This assured that the center lines for the four pins in the shoe and the pivot pin for the lever were parallel to the center line of the motor shaft. It was then certain that

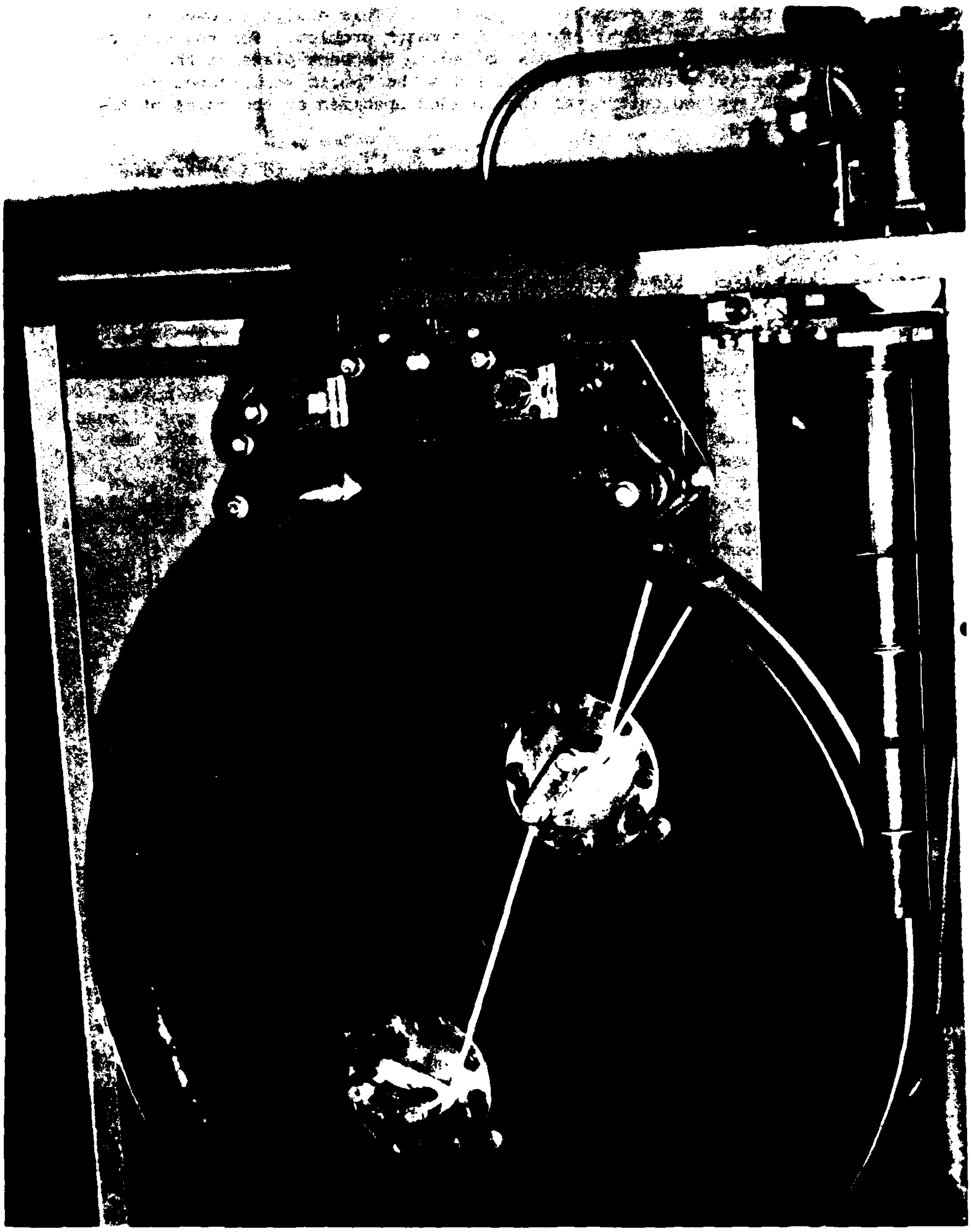


Figure 2A. Photograph of High Speed Abrasion Apparatus in the Kevlar on Kevlar Parallel Test Configuration (3/4 Inch Webbing Installed)

Figure 2B. Close-Up Photograph of Shoe and Abraded Specimen in the Kevlar on Kevlar Parallel Test Configuration

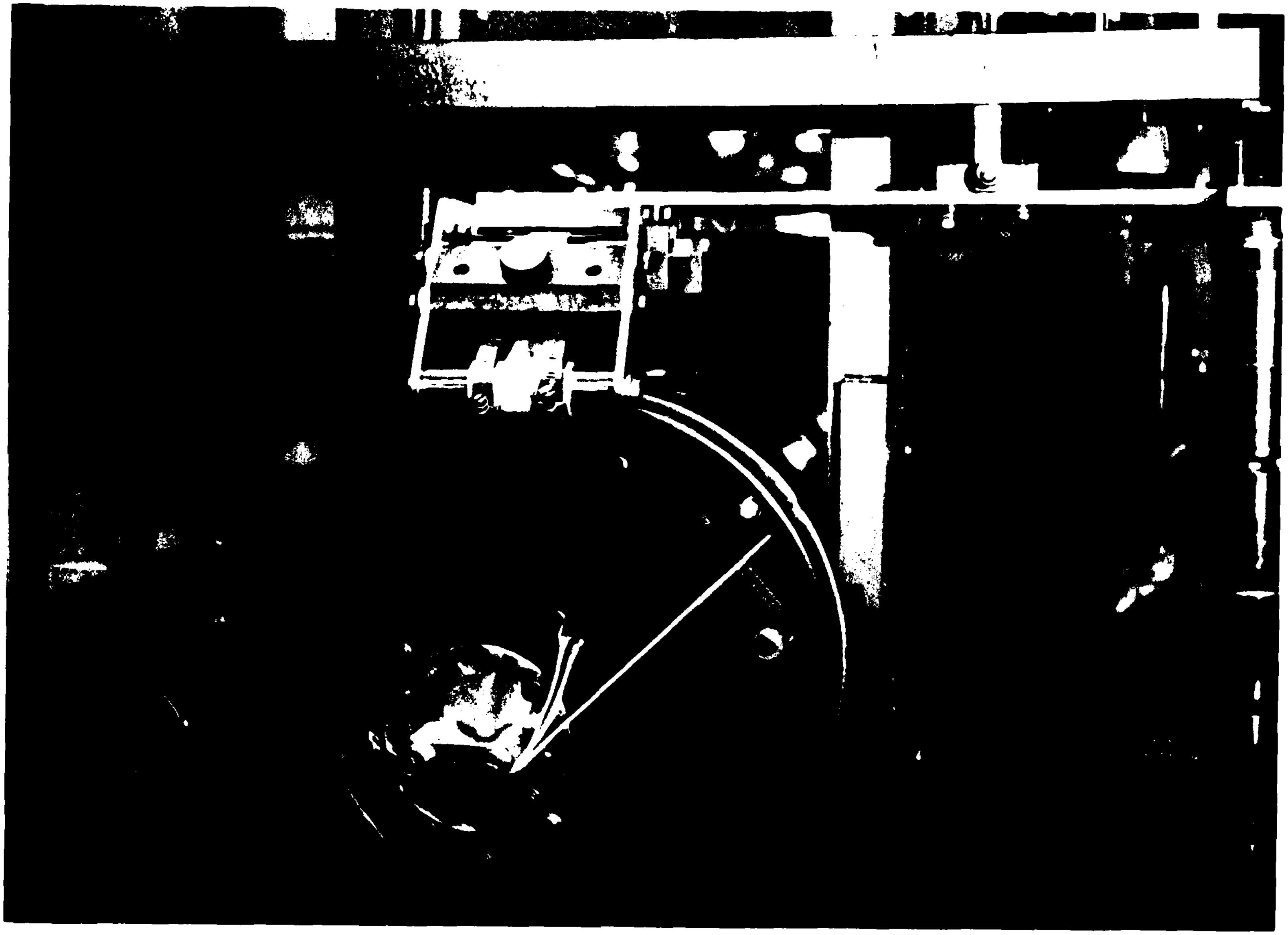


Figure 3A. Photograph of High Speed Abrasion Apparatus in the Kevlar on Kevlar Perpendicular Test Configuration (1 Inch 6,000 Lb Webbing Installed)

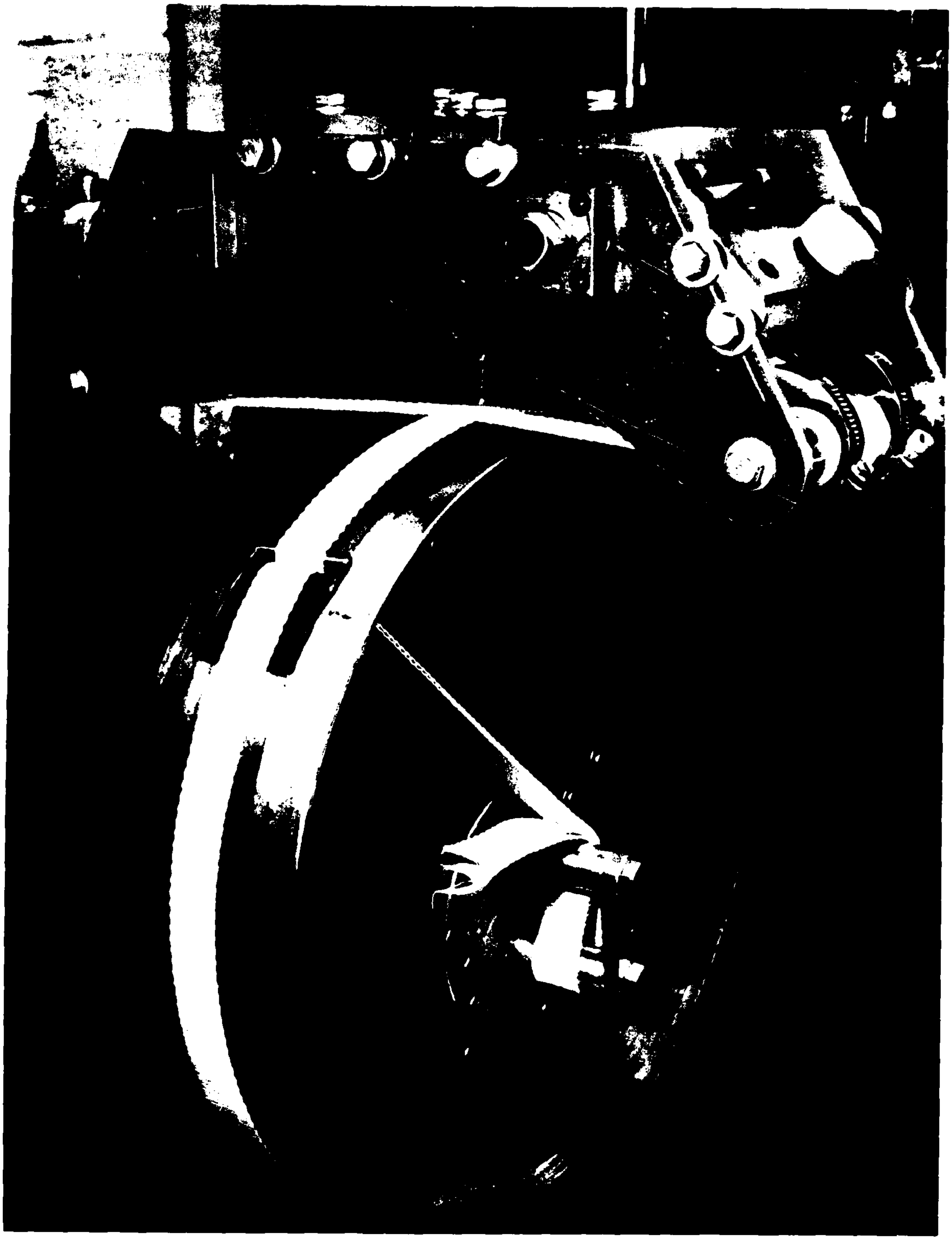


Figure 3B. Close-Up Photograph of Shoe and Abraded Specimen in the Kevlar on Kevlar Perpendicular Test Configuration

the abraded and abrading specimens were actually parallel or perpendicular as the particular test configuration dictated. Both the flat of the wheel rim and the lever and shoe were checked for level along the axis of the motor shaft in order to assure even pressure distribution over the contact area. A number of counterweights had been fabricated based on the contact forces desired and the ratio of distances from the pivot point to the center of the shoe and to the counterweight attachment point. A system for periodically checking the contact force was devised. This system used a spring scale attached to the center of the shoe, vertically above it. Once the counterweight system had been devised, the contact force was adjusted by adjusting the weight of the shoe. The length of contact between the abrading and abraded specimens was adjusted by raising or lowering the pivot point for the lever. It was impractical to obtain a 12-inch contact length with this apparatus. Initially, a 6-inch contact length was used, and this was later reduced to 3 inches. Several blocks of varying thicknesses were machined to fit between the pivot and the frame for this purpose. Checking of the configuration was performed whenever the testing was changed or problems arose in testing.

C. Specimen Installation

The testing procedures were all very similar; however, there were some changes necessary to accommodate peculiarities of some testing. The abraded specimen was mounted on the shoe and centered on the pins. Plastic tubing and hose clamps were fitted to the fixed contact pins and adjusted to the width of the particular material so that subsequent specimen mountings could be done quickly and without concern over the position of the sample. The wheel rim was then marked with an indelible marker, using the edge of the abraded specimen as a guide, in order to facilitate positioning of the abrading specimen on the wheel before each test. The ends of the abrading specimen were passed through the two-pin connector, after positioning of the sample on the wheel, as shown in Figure 1. A torque wrench was used in an attempt to keep the tension in the abrading specimen consistent from test to test. In the Kevlar on Kevlar testing, the two-pin connector which held the ends of the specimen was torqued to 70 ft-lb and the other two-pin connector was torqued to 100 ft-lb. The resultant maximum theoretical tension in the specimen was then calculated to be 2400 lb. Estimates of sample tension show it to be on the order of 1,000 lb. These numbers were kept consistent except where harsh test conditions tended to move the abrading specimen and the values were increased to 100 and 130 ft-lb. In all cases, a fresh abrading surface was used only for each test. In most cases both surfaces of the abrading specimen were used. In the parallel testing with the braids, two abrading specimens were wrapped side-by-side around the circumference of the wheel, and the abraded specimen positioned in the shallow groove formed by the curvature of the two abrading braids in lateral contact with one another. In the testing with abrasive paper, a high torque value of 50 ft-lb was used. As mentioned previously, a PVC block was used to partially close up the opening in the wheel rim. In this case, the two-pin connector closest to the opening was removed and the wheel rebalanced.

Once the abrading material was positioned, it was necessary to adjust the abraded specimen. In operation, the lever was level during the test. The height of the pivot point was adjusted to give the proper contact length (in parallel testing) with the lever in the level position. This was mentioned previously as a part of the alignment procedure before the start of a

test series. Therefore, at the start of each test, the tension adjuster was used to raise the tension in the specimen until the lever was level. This was facilitated by the mounting of a bubble balance on top of the lever. The tension and level were checked by repeatedly lowering the shoe in the same manner which was to be used for the test. The specimen was then marked for limits of contact and direction of rubbing. In the perpendicular configuration, the pivot point was raised as high as possible in order to minimize specimen deflection and avoid contact with the edges of the wheel. The same procedures were followed by leveling the lever before each test.

D. Test Procedure

The actual test procedures used in this program were not exactly as called for in the Statement of Work. Reasons for this will be explained in later sections on testing. Before the start of the test, the contact force was set. Contact forces of 1, 2.5, 5, 10, 15 and 20 lbs were used. Also, the contact speed and contact times were predetermined. Contact times were generally limited to not more than 60 seconds. At the start of the test, the shoe was raised and the wheel brought up to speed. The shoe was then lowered, bringing the specimens into contact. A stop watch was used to measure the duration of contact and the shoe was raised at the proper time. Two techniques were used for lowering the abraded specimen into contact with the abrading material. Normally, this was performed by a quick release of air pressure in the cylinder and free fall of the abraded specimen from a height not greater than 1 inch above the abrading material. In the perpendicular test configuration, the high tension in the abraded specimen caused problems with bouncing after impact and a slow release of air was necessary. This slow dropping technique was also used in some testing of ribbons in the parallel-on-concrete configuration.

After the test, the specimen was removed and allowed to condition to standard conditions (70°F and 65%RH) overnight. The specimen was then tensile tested using techniques developed in the initial portion of this contract[2]. The value of breaking strength was normalized using a control value for the material generated from tests performed with specimens taken from different locations in that particular roll of material. This method of control value generation allowed checking the strength of the material as the testing proceeded and investigation of variability within each roll and between rolls of the same material. After a series of tests had been run and the abraded specimens tested, a curve of percent strength loss as a function of contact time was plotted for that particular material and configuration. The end result was, therefore, a family of curves of this type for each test configuration and material and a range of testing speeds.

In most cases, the contact force was kept constant throughout this range of speeds for each material and test configuration. The individual test results are given in Tables 6, 7, 9 and 10 and the curves are shown in the corresponding Figures. Measurement of changes in weight and thickness was not performed for several reasons. Broken fibers imbedded in the material in the abraded area contributed to both the weight and thickness of the material in that area but not the strength. Fibers in the weave outside of the abraded area, may have had no effect on strength due to the breakage in the abraded area, but did contribute to the specimen weight. Most importantly, strength loss mechanisms other than fiber breakage contributed significantly to strength loss without reducing weight or thickness. These mechanisms are discussed in later sections of this report.

SECTION IV

PRELIMINARY TESTING

A. Exploratory Investigation of Test Conditions

Initially, tests were run at the highest speed (240 fps) in order to get the maximum abrasion. Contact forces of 5 to 15 lb and times between 5 and 30 seconds were used. The 1 inch 6,000 lb Kevlar webbing was used for this testing. The maximum strength loss recorded was approximately 50% using a contact force of 5 lb and a contact time of 30 seconds at this speed. Failures of the abraded specimen always occurred in the 6-inch abraded length which was centered between the jaws. Thickness measurements indicated uneven wear along the abraded length with the maximum usually occurring at the trailing edge of the abraded length. Maximum change in thickness for the abraded specimen was approximately 20%.

Tests at a lower speed (160 fps) were similar to those at the higher speed. Maximum thickness change also occurred at the trailing end of the abraded length on the abraded specimen. Contact forces of 5, 10 and 15 lb and contact times of 45 seconds to 5 minutes were used in this testing. Initially the conditions were set at 5 lb contact force and 45 seconds contact time. This yielded the same total rubbing length (7200 ft) that was used in the harshest conditions (5 lb-30 sec) at the higher speed. In this test, however, there was negligible strength loss for 3 tests. This indicated a substantial velocity effect. Increasing the contact time to 5 minutes yielded only a 10% strength loss. This indicated that higher contact forces would be necessary for testing at the slower speeds. Several tests were then run with a contact force of 15 lb and several contact times between 1/2 and 2 minutes. Good correlation was found between contact time and strength loss. Several tests were also run using 5, 10 and 15 lb contact force and 2 minutes contact time. Again, good correlation was found between contact force and strength loss. However, it should be mentioned that only one test was run at each condition. During all of this testing, the same specimen was used on the wheel. Indications, at this point, were that this technique did not affect the amount of abrasion of the abraded specimen.

B. Specimen Scorching

After some of the tests, a browning of both samples was observed. This browning seemed to increase with increasing severity of the test conditions and was always more evident on the abraded specimen than the abrading specimen. Also, browning on the abraded specimen was more noticeable near the trailing end of the abraded length. This browning may have been the result of scorching due to heat buildup during the test. However, the specimen was never excessively hot after the wheel stopped (approximately 1 minute after the end of the test) as usually it was only warm to the touch and never too hot to touch.

Magnification and inspection of the abraded area revealed that the browning or scorching was present in the fibers on the surface of the specimen. Many broken fibers were evident upon inspection as expected. The brown fibers seemed to have lost almost all of their strength and could probably be considered equivalent to broken fibers as far as specimen strength loss

was concerned. Tensile failures of these specimens almost always occurred in the region of maximum browning. It was believed that this browning was a scorching of the fibers due to intense localized heating of the fabric knuckles. However, this theory had not been confirmed at that time.

C. Strength Loss in the Abrading Specimen

Tensile testing of the abrading specimen after abrasion at the highest speed yielded essentially no loss in strength. Two breaks were made from each specimen. It was necessary, in all tensile tests, to avoid the area where the specimen had been wrapped around the small radius in passing through the slot to be clamped inside the wheel. This was a point of high abrasion and caused low values of breaking strength if it was included in the specimen free length. Because of the lack of any strength loss in the moving sample, it was suggested to the Project Engineer that tensile testing of this sample be discontinued to permit a more complete study of the effects of contact force and time on the abraded specimen.

D. Repeated Use of the Abrading Specimen

A series of tests was run for the purpose of investigating the possibility of using the abrading specimen for several tests. Tests were run at the highest speed (240 fps) using 10 lb contact force, 30 second contact time and the 1 inch wide 6,000 lb webbing as the test specimen. Test results are given in Table 4. Four tests were run using a fresh specimen on the shoe for each test and retaining the same abrading specimen. The results of the first two tests were similar, with the abraded webbing sustaining a strength loss of approximately 25%. The next two tests were also similar to each other but the strength loss in the webbing was less than 10%. It seemed obvious then that even though the abrading specimen did not sustain damage which resulted in a measurable strength loss, as seen previouously, its abrasive power was affected by these tests. A fifth test further strengthened this conclusion. This test was run with the same test conditions except the abrading specimen was turned over to expose the unabraded side of the specimen. As with the first two tests, a strength loss of approximately 25% was recorded in the abraded specimen. As a result of this test series, the test procedure always involved the use of fresh abrading surface for each specimen. However, both sides of the abrading specimen were used for abrasion. This was possible since tensile testing of the abrading specimen showed no measurable strength loss because the abrasive damage was a function of contact length and the ratio of contact lengths for the abrading and abraded specimens was as great as 16. The recommended procedure was to eliminate tensile testing of the abrading specimen and use both surfaces for abrasion.

E. Abrasion of a 1 Inch Wide 6,000 Lb Kevlar Webbing in the Kevlar on Kevlar Parallel Configuration

A series of tests was run at the highest speed (240 fps) using the 1 inch 6,000 lb webbing as the test sample. The test conditions were varied in order to determine the relationships between strength loss and contact force and time. Contact forces of 10, 15 and 20 lbs were used. Contact times of 5, 15, 30 and 60 seconds were used. Three tests were performed at each condition. Both sides of the abrading specimen were used and a fresh abrading surface was used for each test. The tension in the abraded specimen increased with increasing contact force in order to obtain level running

conditions and a 6-inch contact length. All specimens were conditioned to standard conditions (70°F, 65%RH) before abrading and also before tensile testing. The results of this testing are given in Table 5 and Figure 4A*.

TABLE 4

RESULTS OF INVESTIGATION OF REPEATED USE OF ABRADING SPECIMEN USING THE 1 INCH 6,000 LB KEVLAR WEBBING ABRADED IN THE KEVLAR ON KEVLAR PARALLEL CONFIGURATION

Test No.	Speed (fps)	Contact Force (lb)	Contact Time (sec)	Rupture Force (lb)	Abraded Specimen Strength Loss (%)**
1*	240	10	30	4400	27
2	240	10	30	4450	26
3	240	10	30	5400	10
4	240	10	30	5600	7
5*	240	10	30	4500	25

*Abraded with fresh abrading surface (see page 15).
**Control value for rupture strength taken as 6,000 lb.

TABLE 5

ABRASION OF A 1 INCH 6,000 LB KEVLAR WEBBING AT A SPEED OF 240 FPS IN THE KEVLAR ON KEVLAR PARALLEL CONFIGURATION

Contact Force (lb)		Breaking Strength (lb)			
	Contact Time (sec)	5	15	30	60
10		4750	4800	3150*	2400*
		5400	4600	3350*	2450*
		5100	4700	2950*	2000*
	Avg.	5080	4700	3150	2280
	Strength Loss (%)	13	19	46	61
15		5250	4200	4500	3650*
		5150	4350	4250	3000*
		5150	Bad Brk.	3450*	3000*
	Avg.	5180	4275	4070	3220
	Strength Loss (%)	11	27	33	47
20		3750	2400		
		3800	1850		
		3550	2350		
	Avg.	3700	2200		
	Strength Loss (%)	39	64		

*Piling observed on unabraded surface (see below).

*Code for Figures on page xi.

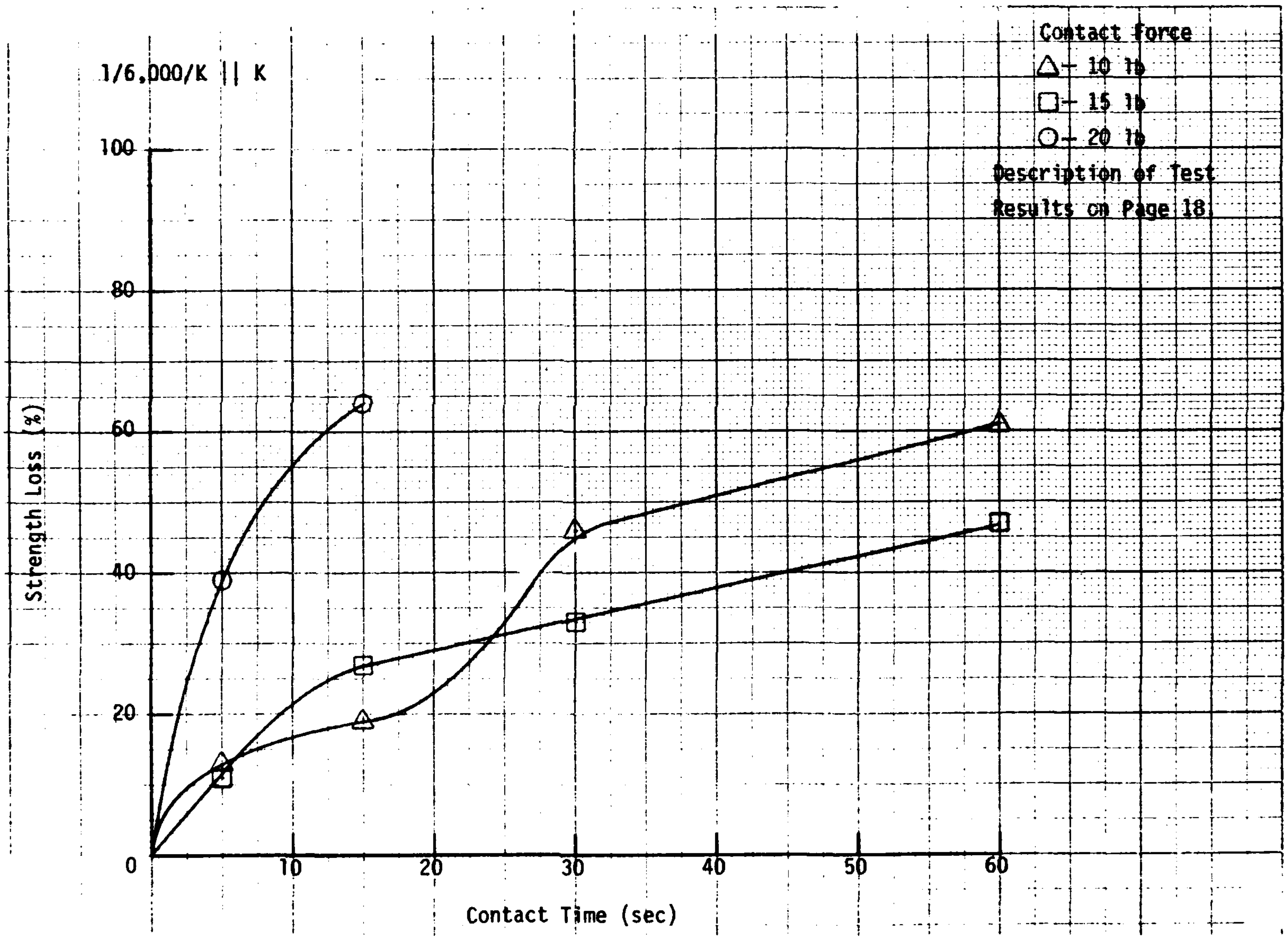


Figure 4A. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration at a Speed of 240 fps Using Various Contact Forces and a 6 Inch Contact Length

F. Development of a Pile on the Unabraded Surface of Abraded Specimen

In the course of this work, an unexpected phenomenon was observed. In addition to expected wear in the form of broken and scorched filaments on the abraded surface, a fuzzing or piling was observed on the opposite unabraded surface of this area (i.e., the back of the specimen which was not in direct contact with the flywheel) under certain running conditions. Closer inspection of this phenomenon revealed that loops of filaments were protruding from the yarn knuckles giving the yarn an open appearance. Figure 4B shows photographs of the piled and unpiled surfaces of a 1 inch 6,000 lb webbing. This phenomenon was first observed during abrasion testing of Kevlar webbings with the hex-bar abrader. It was reported at that time in Progress Report No. 5, January 1975, Contract No. F33615-75-C-5168 [1]. It has also been observed in other work during rolling flex cycling of Kevlar and nylon webbings at both low and high speeds where direct abrasion was not involved. This piling resulted in length differentials between the filaments, uneven distribution of tension within the yarn and therefore low values of breaking strength for the structure. This is evident from the values of breaking strength shown in Figure 4A and Table 5 which will be explained later in this section. In the case of flex cycling, the piling was believed to be the result of cyclic compression of the yarns. With the high speed abrasion apparatus, there may have been some undetectable fluttering of the abraded sample coupled with the friction forces between the samples which caused the compression of the yarns on the unabraded surface. This theory was further strengthened by the fact that increasing the tension in the abraded specimen reduced or eliminated this phenomenon. It was also possible that a light coating on the unabraded surface could have eliminated it. It was obvious that this phenomenon was not completely understood. However, the scope of the program would not allow for an in-depth investigation. It was therefore decided that this phenomenon should be avoided, by selection of appropriate test conditions, wherever possible, in all further testing.

G. Preliminary Test Results

As is evident from Figure 4A and Table 5, there were some peculiarities present which required some explanation. In general, there was an expected increase in strength loss associated with increasing contact time and force. The knee present in the 10 lb curve indicated the effects of piling. Table 5 shows that piling was observed at 30 seconds but not at 15 seconds when 10 lb contact force was used. This was due to a loss in tension during running which was observed as a change in the angle of the lever arm with time as the test was run. At the start of the test the lever arm was level. As the test was run, the shoe lowered and the arm moved out of level. At some point the tension in the abraded specimen became low enough to allow piling to occur. With 10 lb contact force, this occurred between 15 and 30 seconds contact time and the strength loss is evident in Figure 4A. Using 15 lb contact force, piling began at approximately 30 seconds. Table 5 shows that piling occurred in one of the three specimens tested at this condition. The strength loss sustained by this specimen was much greater than that found in the specimens having only abrasive damage. Also, the strength loss in the two specimens where piling was not present, was not significantly different from losses found after only 15 seconds of contact time. This indicated that the rate of abrasive damage decreased significantly with time and that the curves in Figure 4A should level off to near zero

Unpiled Surface

Piled Surface Generated at a Speed of 120 fps for 60 Seconds Using a Contact Force of 2.5 Lb and a Contact Length of 6 Inches

Figure 4B. Photographs of the Surface of a 1 Inch 6,000 Lb Kevlar Webbing Showing the Effect of Piling on the Position of the Fibers in the Yarns

slope at some time if piling was not present. The lack of an inflection in the 15 lb curve is due to the relatively small influence of the specimen which showed piling on the average at 30 seconds. If additional tests were run at 25 and 35 seconds, there would probably have been a significant difference in measured strength loss because of piling, resulting in an inflection in the curve. Also because the tension in the abraded specimen was lower when using 10 lb contact force than when 15 lb was used, piling occurred sooner and was much more serious with the lighter load.

Tests run using 20 lbs contact force yielded high strength losses in very short times. Piling was not evident in these specimens but scorching was much more severe at this load than at 10 or 15 lb. No scorching was recorded in tests at 10 lb contact force and only mild scorching was seen at 15 lb. Specimens tested at 20 lbs were scorched so badly that brown spots were detectable on the unabraded surface. The tensile breaks in this series were poor. Specimens abraded for 5 seconds broke in the center leaving both edges intact. Specimens abraded for 15 seconds broke with random popping of warp yarns. This was believed to be due to the severe scorching found under these conditions. One attempt was made to increase the contact time to 30 seconds at this load but the abrading specimen loosened on the wheel and no further attempts were made.

Breaks in this series always occurred in the abraded length except for one bad break. Most of the specimens abraded with 10 lb contact force ruptured cleanly near the leading edge of the abraded length. However, specimens abraded for 60 seconds at this load failed in the center of the abraded length and two of the three breaks were tears. This was probably due to the severe piling at this condition. In general, specimens abraded with 15 lb contact force also ruptured cleanly near the leading edge of the abraded length. As mentioned previously, specimens abraded with 20 lb contact force failed incompletely and non-simultaneously. All failures occurred at the trailing edge where the scorching was most severe.

H. Changes in Testing

On June 25, 1979, the Project Engineer visited FRL to discuss procedures to be followed for the remaining testing. It was decided at that time, that the piling phenomenon mentioned previously should be avoided, if possible, during abrasion testing. In order to do this, the length of contact between the two samples was decreased from 6 inches to 3 inches resulting in increased tension in the abraded specimen. It was expected that the increased specimen tension would reduce or eliminate piling, and subsequent tests carried out under conditions which produced it when the contact length was 6 inches showed that this was so. This contact length was adopted as standard for all testing in the parallel configuration and was used in conjunction with test procedures outlined previously.

SECTION V

KEVLAR ON KEVLAR (NYLON ON NYLON) PARALLEL ABRASION

A. 1 Inch 6,000 Lb Kevlar Webbing

The 1 inch 6,000 lb webbing was used to investigate in detail the relationship between strength loss and contact time and force at a speed of 240 fps. A contact length of 3 inches was used and contact forces and times ranged from 5 to 20 lb and 5 to 60 seconds. Figure 5 shows the results of this testing. Table 6 also shows individual test results and conditions. As was expected, abrasive damage measured as strength loss increased with both increasing contact time and force. It also appeared that contact force contributed more to the strength loss than did contact time. This was evidenced by an increase in scorching with contact force as well as strength loss. It seemed that a 50 lb contact force could have caused almost immediate failure at these running conditions. The tensile breaks in this series were typically simultaneous breaks leaving one or two yarns on each edge intact, indicating the lack of contact at the very edges. This was expected due to the decrease in thickness of the as-woven material at the edges.

A comparison of these curves with those in Figure 4A showed clearly the effect of changing the contact length from 6 inches to 3 inches. The sharp rise in the 10 lb curve between 20 and 30 seconds for a contact length of 6 inches was attributed to the development of piling. No such evidence is present in the curves obtained with a 3 inch contact length, and no piling was observed. It was also apparent that the amount of abrasion was roughly dependent upon pressure, indicated by the similarity of the 20 lb, 6 inch and 10 lb, 3 inch curves, as well as the initial part of the 10 lb, 6 inch and 5 lb, 3 inch curves.

Figure 6 shows the results of the testing performed at speeds of 160, 120 and 80 fps in the Kevlar on Kevlar parallel configuration. A contact force of 15 lbs was used in this test series. The testing performed at 240 fps at the same loading condition and abrasion configuration is also included in this Figure. The curves for testing performed at speeds of 120 and 80 fps show a sharp strength loss in the first fifteen seconds, then becoming linear after fifteen seconds. This could possibly indicate that the surface of the specimen was becoming smooth as the high ridges from the filling yarns were worn flat. Also, the impact at the start of the test could have caused a high initial rate of abrasion. Scorching of these samples was barely noticeable through the first fifteen seconds. At sixty seconds, however, the scorching was severe enough to give a brown tint to the unabraded surface of the abraded specimen. Most of the tensile breaks in this series occurred near the trailing edge where the scorching was most severe.

An anomoly exists in this data, however. The shape of the curve corresponding to testing performed at 160 fps is different from those obtained at other speeds. Strength losses were very high in the first two seconds of contact. There is a sharp knee in the curve at this point and essentially no strength loss was found beyond this point. Scorching increased with increasing contact time up to about 15 seconds and then remained fairly constant. This curve actually crosses the curve corresponding to testing at 120 fps. The major difference, apart from the test speed, in these two test

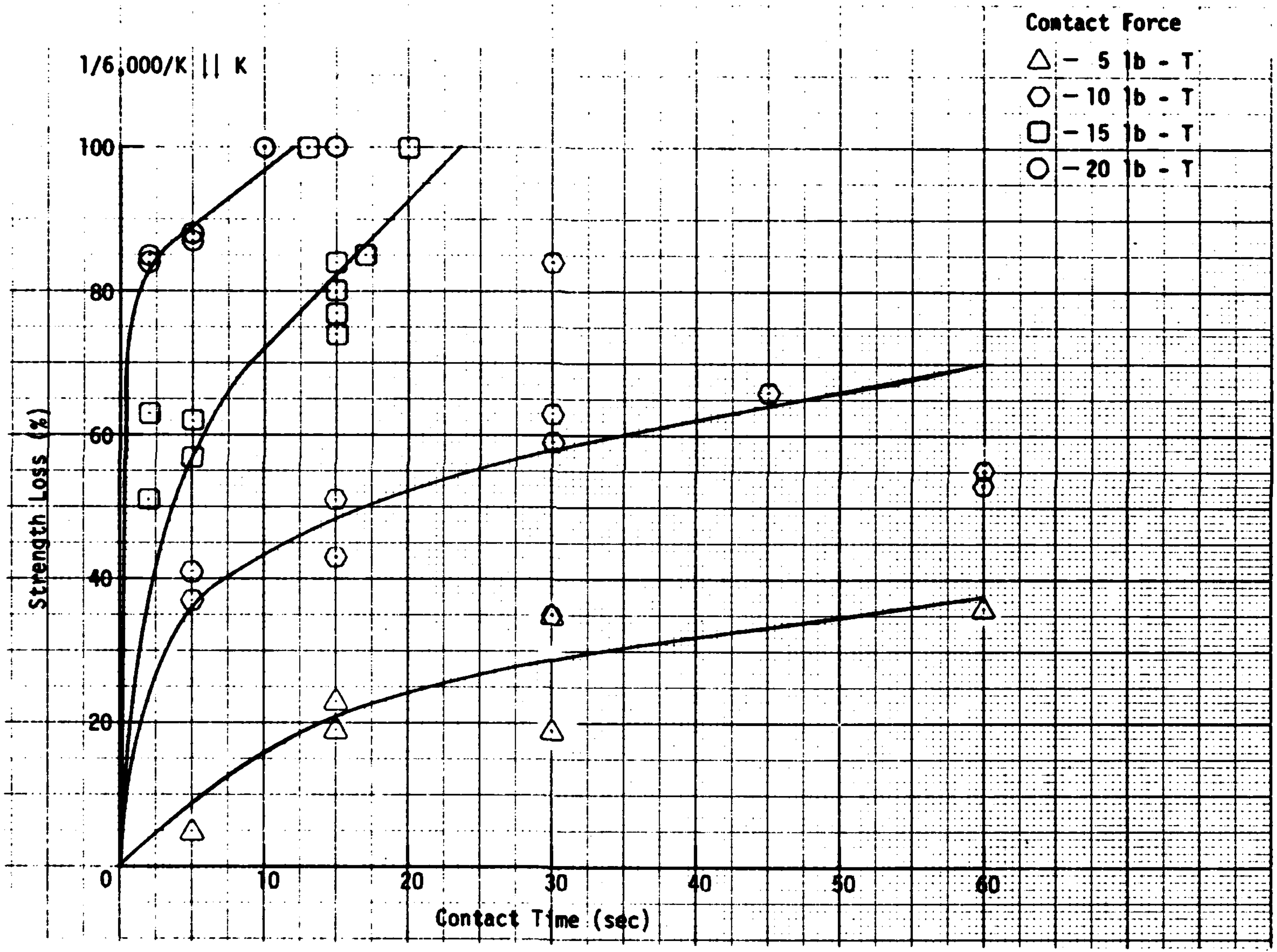


Figure 5. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration at a Speed of 240 fps Using Various Contact Forces and a 3 Inch Contact Length

TABLE 6

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON ON NYLON) PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 2	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	5	240	5,760		5		19[1] 23			35[1] 19					36
	10	240	5,760		41[1] 37		51[1] 43			35 63 84[2] 59[2]			66[2]		55[2] 53[2]
	15	240	5,760	51 63	57[1] 62	100*	77 74 84 80[2]	85[2,3] 100[2]							
	20	240	5,760	85 84	87 88	100[1]	100								
	15	160	6,040	55[4] 51[4]	58[2] 58[4]		56			52 58[2]			54 65[2]		59 58[2] 59[4]
	15	120	5,790		29		48 42			55					59 67
	15	80	5,790		8		40 33			40					50 59

*Footnotes 2 and 10.

Table 6 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON AND NYLON) PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds)											
				2	5	10	15	20	25	30	35	40	45	50	60
3/4 inch 500 lb Kevlar Webbing	5	80	605		28		33 38			32 41					37 43
	5	120	605		40		36 46			55 57					60 60
	5	160	605		29		45			44			50		55
	5	240	605		42		50			49			55		54
1 inch 9,000 lb Kevlar Webbing	20	80	10,560												0
	20	120	10,560		42 41 35		48 52			64 60					79 73
	20	160	9,930	47[5]	53		47			58			55 57		64
	20	240	9,930	65[5]	68		64			68			70		56 66

TABLE 6 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON AND NYLON) PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Contact Value (pound)	Contact Time (seconds) 2	5	10	15	20	25	30	35	40	45	50	60
2,000 lb Kevlar Braid	5	40	2,200		0										
	5	80	2,230		37 35	38	32 49	47		47 50					63
	5	120	2,230		50 50[7]	66 59[8]	65 62 61[8]	67 61[8]	66[8]	96[6] 68[8]			81[8]		
	5	160	2,270		64[7]		65[7] 69[7]			71[7]			74 71		76
	5	240	2,270		74	82	80		93[9]	91					
1 Inch 6,000 lb Nylon Webbing	15	40	6,900		1		0	3	37 10	5 0	55	74 57	70 50	94	
	15	80	6,690		100										
	5	80	6,690			25	43 43 44	50		77 80 75					
	5	120	6,690		100										
	2.5	120	6,900		56	71	80 75	83		96 97					

TABLE 6 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON AND NYLON) PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Contact Value (pound)	Contact Time (seconds) 2	5	10	15	20	25	30	35	40	45	50	60
2,000 lb Nylon Braid	5	40	2,450							8	18	99		61	
										94		95			97
										96		98			
										2			76		
	1	80	2,450		2					2	87		1		2
	2.5	80	2,450		97		100								
					0		100								
							61								
							99								

Footnotes:

1. Control value 6,050 pounds.
2. Control value 6,140 pounds.
3. Contact time 17 seconds.
4. Control value 6,045 pounds.
5. Control value 10,140 pounds.
6. Contact time 26 seconds.
7. Control value 2,170 pounds.
8. Control value 2,250 pounds.
9. Contact time 23 seconds.
10. Contact time 13 seconds.

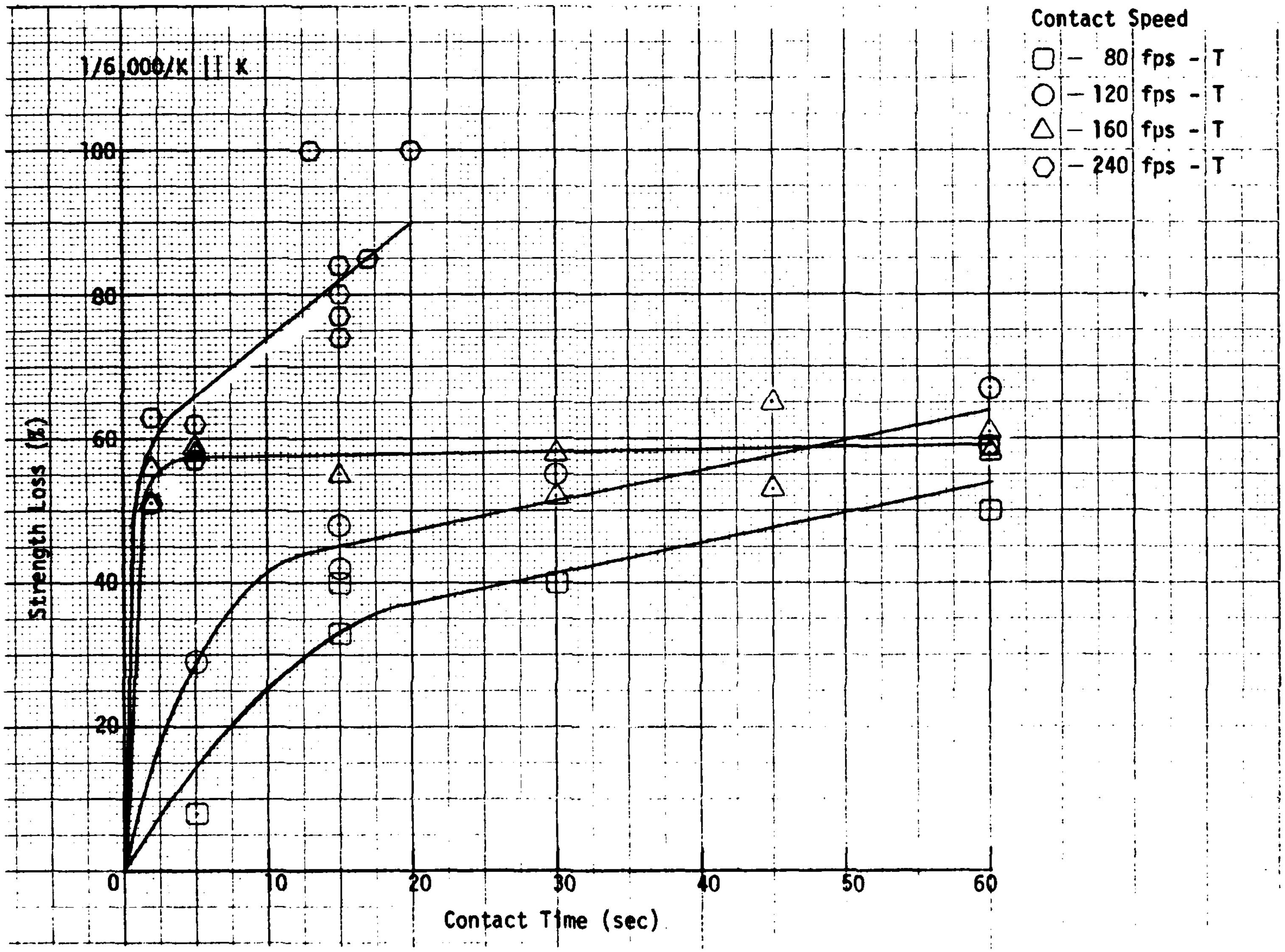


Figure 6. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 15 Lb and Various Contact Speeds

series was the tension in the abraded specimen. Because the tests performed at 160 fps were done with the 32 inch diameter wheel, the deflection in the specimen was only half of the deflection in the specimens tested at 120 fps using the 16 inch diameter wheel. This meant that the tension in the specimens tested at a speed of 160 fps was roughly twice the tension in the specimens tested at 120 fps*. This indicated a substantial tension effect, possibly due to a change in surface characteristics. The reason for the shape of the curve at 240 fps is not clear. This may be due to the increased heating and scorching. The reason that this curve appeared under these conditions is not known. If this was an effect of tension, then the curves in Figure 5 are not true representations of the relationship between strength loss and contact force since specimen tension is directly related to contact force. It was also possible that these particular conditions resulted in a swift smoothing of the fabric surface and therefore a sharp decrease in the coefficient of friction, reducing fiber wear to near zero and/or resulting in a balance between heat generation and heat loss.

B. 3/4 Inch 500 Lb Kevlar Webbing

The 3/4 inch 500 lb Kevlar webbing was abraded at speeds of 240, 160, 120 and 80 fps. A contact force of 5 lb was used. Only mild scorching was seen in all testing. This was evidenced by the relatively flat curves shown in Figure 7. The tensile breaks were also good, in general. Most of these occurred near the center of the abraded length also indicating a mild heat effect at most. There appeared to be a small effect of test speed on strength loss when Figure 7 was studied. Again, the apparent effect of specimen tension was seen as a higher strength loss in specimens tested at 120 fps than at 160 fps and in some cases even 240 fps. In general, however, these curves showed typical high strength loss initially and a decrease in the rate of abrasion with increasing contact time.

C. 1 Inch 9,000 Lb Kevlar Webbing

Initially, the 1 inch 9,000 lb webbing was abraded at 120 and 80 fps. Contact forces of 15 and 20 lbs were used. No significant strength loss was seen at 80 fps for either loading condition. Initially, a contact force of 15 lb was used. Problems with uneven scorch patterns at this load were solved by increasing the contact load to 20 lb. This was most likely due to the material construction, which is a twill with a center reversal. The fabric surface tended to go out of plane when this type of Kevlar construction was tensioned. This caused an uneven pressure distribution across the width of the specimen and thus uneven scorch patterns. The center reversal also divided the specimen into two different weave patterns and, therefore, surface characteristics across the width of the material. By increasing the contact force and keeping opposite weave patterns of the abrading and abraded specimens in contact, the pressure distribution could be made much more even as evidenced by the photograph in Figure 8. The photograph shows four specimens abraded at 120 fps using 20 lb contact force and contact times of 5, 15, 30 and 60 seconds. Close inspection of the photograph reveals the two different weave patterns on the surface of the specimens. Also evident in this photograph is the evenness of the scorching, the increase in scorching with increasing contact time, and the increase in contact length with increasing contact time. The leading edges of these specimens are aligned on

*See also Section IX, page 110.

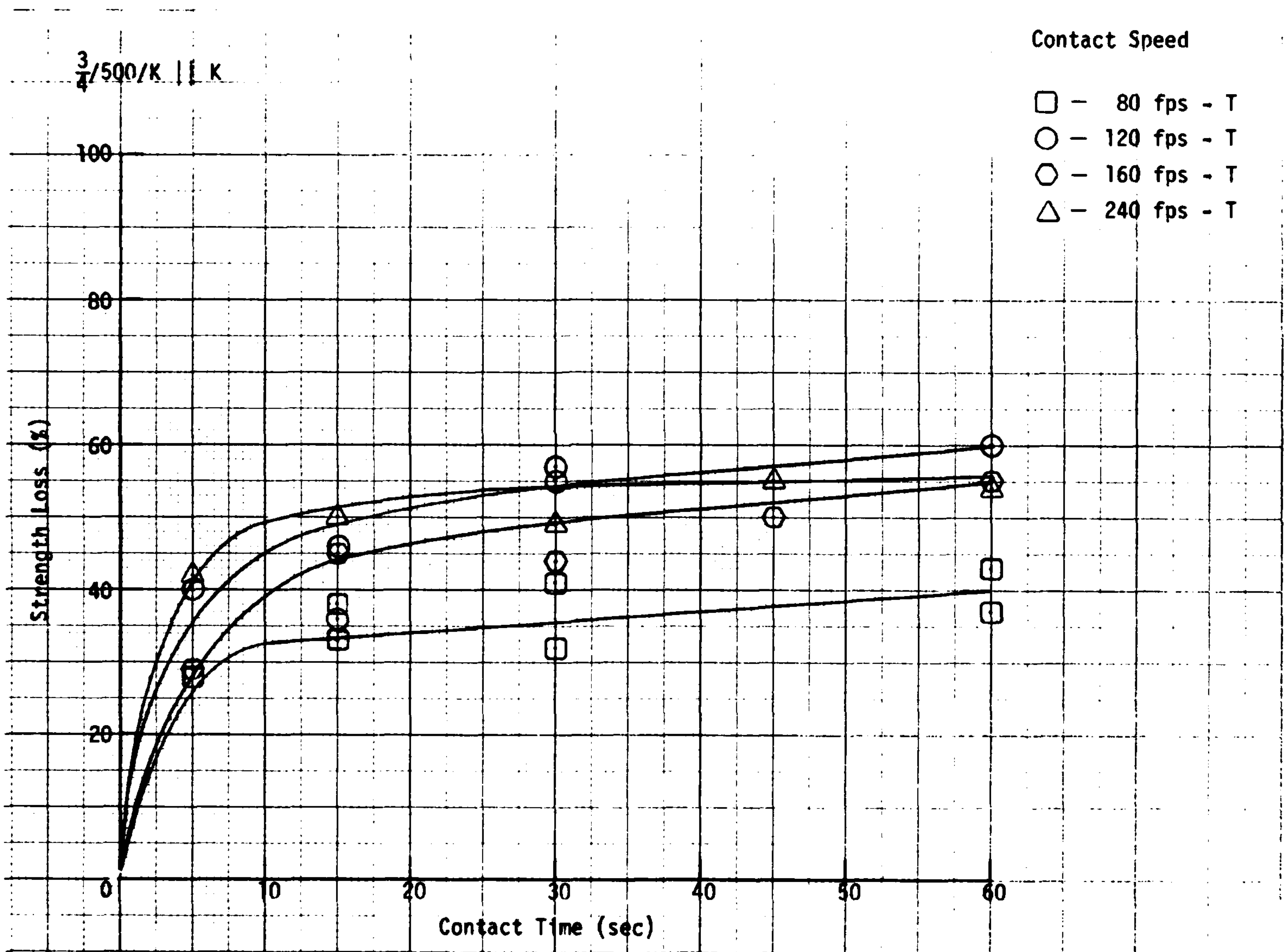


Figure 7. Strength Loss as a Function of Contact Time for a 3/4 Inch 500 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

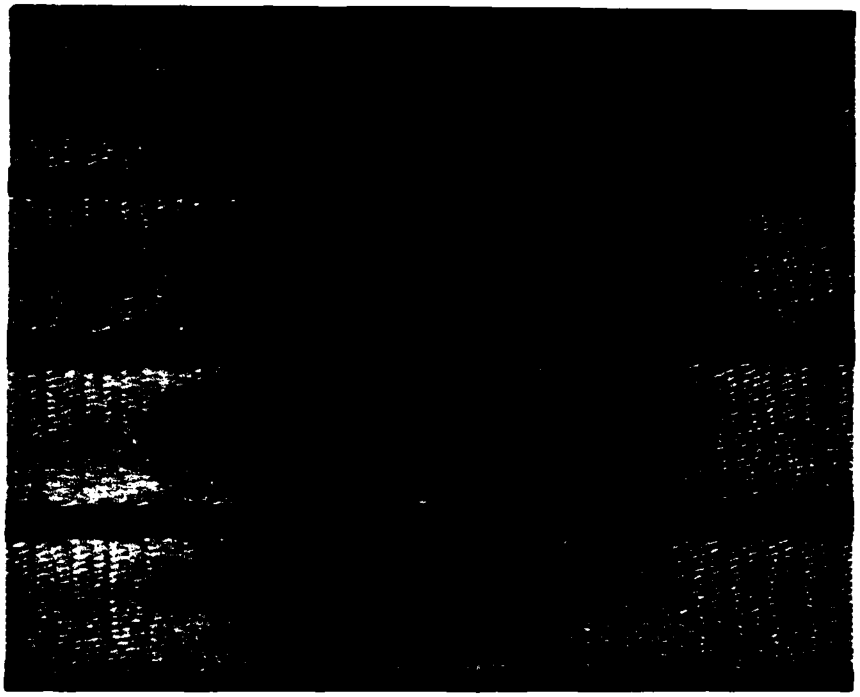


Figure 8. Photograph of Four Samples of 1 Inch 9,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration at 120 fps with a Contact Force of 20 Lb Showing Increase in Scorching with Increase in Contact Time

the right hand side of the scorching in the photograph and the length of the scorching is shown increasing as the specimen wore down with longer contact times. As mentioned in a previous section, as the specimen wears, the lever arm runs out of level (tilts downward) resulting in an increase in contact length and, therefore, scorch length, occurring mostly at the trailing edge.

The results of the testing are presented in Figure 9. The results are given for testing at 240, 160 and 120 fps with a contact force of 20 lb. The testing at 120 fps with a contact force of 15 lb also resulted in strength losses, but the uneven scorching caused poor tensile breaks and high variation in test results. The tests conducted at 80 fps showed no significant strength loss. This was most likely due to the lack of scorching at this speed. The curves presented in Figure 9 are similar to other curves presented here. A non-linear portion of the curve up to 15 seconds is followed by a linear portion of the curve up to 60 seconds. This indicated a reduction in the rate of abrasion after 15 seconds due, presumably, to a change in the coefficient of friction. The tensile breaks of specimens abraded at 120 fps were generally poor. The severity of the scorching weakened the specimen to the point where the specimens tore from one edge to the other. The breaks typically occurred near the trailing edge where the maximum scorching normally occurred. The severity of the scorching and poor tensile breaks was the reason for such high strength losses at 120 fps when no loss was seen at 80 fps.

The testing at speeds of 240 and 160 fps was somewhat different from testing at 120 fps. Specimens blackened with scorching almost immediately and the scorching did not increase with increasing contact time. In some cases, a bonding of black fibers was seen indicating the presence of melting. Exposure of Kevlar to high temperatures usually results in formation of an oxidative char as has been seen previously. It has been speculated, however, that if oxygen were not present or if the rate of heating exceeded the rate of oxidation, melting could occur. Also, pressurization lowers the melting point of Kevlar and could cause melting to occur before oxidation at high temperatures. Attempts to produce melting in Kevlar with a differential scanning calorimeter failed due to a change in the molecular structure as hydrogen was absorbed by the material.

Tensile breaks of specimens abraded at 160 and 240 fps were generally poor, occurring as tears. Inspection of Figure 9 shows the effect of immediate scorching as a high initial strength loss and drastic decrease in the rate of abrasion, again indicating a change in the coefficient of friction. A minor speed effect was found between the testing at 160 and 240 fps. The apparent effects of tension again resulted in higher strength losses in some specimens abraded at 120 fps than 160 or 240 fps. The data presented here does appear to be consistent and strength losses were relatively unaffected by the test speed.

D. 2,000 Lb Kevlar Braid

Testing of the braid in the parallel configuration proved to be a difficult task because of problems with the abraded braid slipping to one side of the abrading braid. It became necessary to wrap two braids on the wheel and butt them closely together. This provided a very shallow channel for the abraded specimen to run in. The results of the testing in this configuration

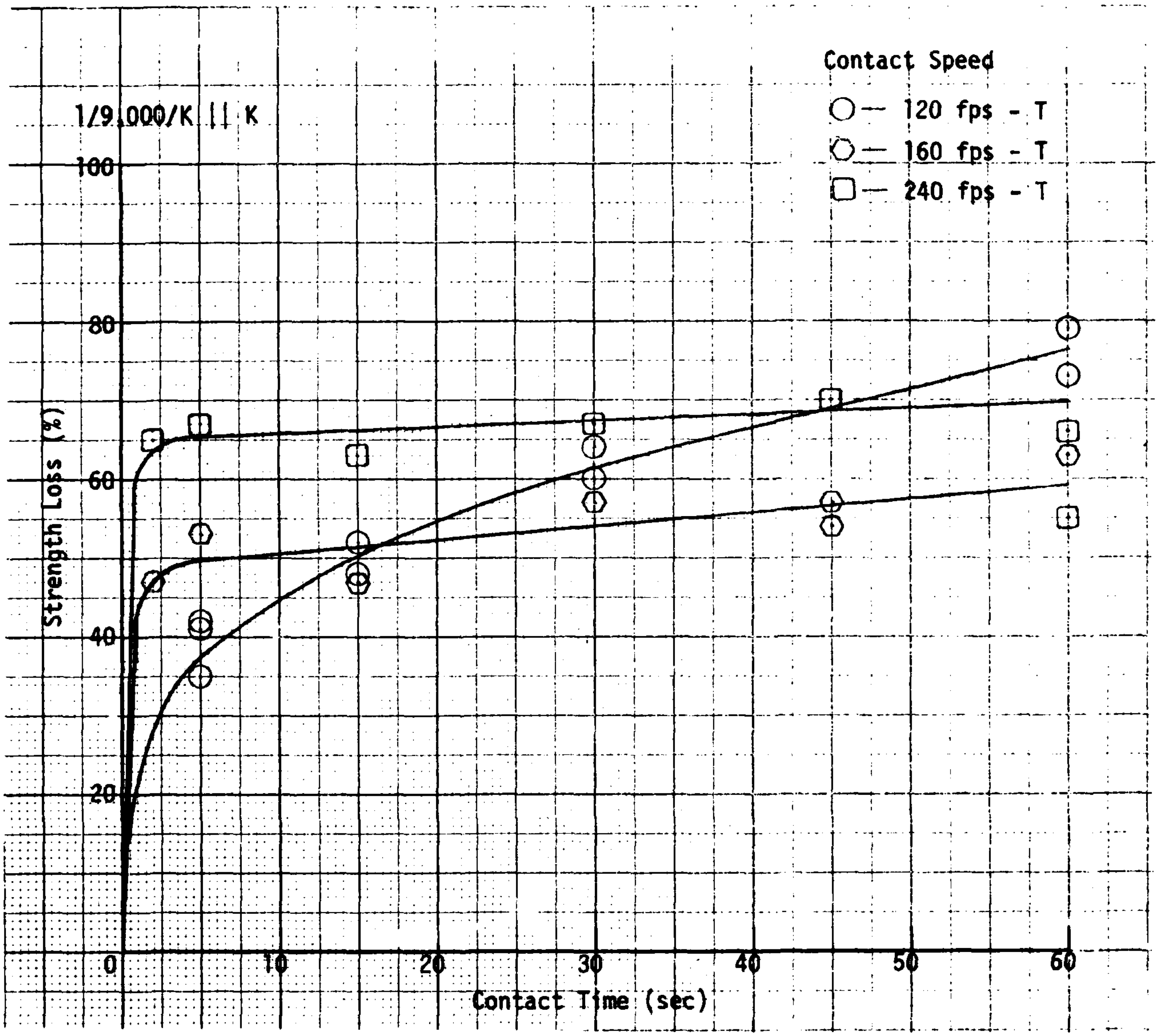


Figure 9. Strength Loss as a Function of Contact Time for a 1 Inch 9,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 20 Lb and Various Contact Speeds

are shown in Figure 10. Tests were performed at speeds of 240, 160, 120, 80 and 40 fps using a contact force of 5 lb. No strength loss was found in specimens abraded at a speed of 40 fps. Specimens abraded at 120 and 80 fps showed an increase in scorching with increasing contact time. These curves exhibit good parallelism in the linear region and reasonably low variability. The specimens abraded at 240 and 160 fps showed severe scorching almost immediately and some apparent melting at long contact times. The curve representing tests performed at 160 fps showed a low rate of abrasion after a high initial strength loss as was seen before with other Kevlar materials. The apparent effect of tension is again seen as higher strength loss in some specimens abraded at 120 fps than some abraded at 160 fps. In all, however, the effects of speed do not appear to be great although there certainly is a significant speed effect present in the data. The effect of tension could be greater than the effect of speed for this braid in this testing.

E. 1 Inch 6,000 Lb Nylon Webbing

The 1 inch 6,000 lb nylon webbing was abraded initially at 120 and 80 fps in the nylon on nylon parallel configuration. Initially, a contact force of 15 lb was used in order to compare results with those for the 6,000 lb Kevlar webbing. Testing at this loading and a speed of 80 fps resulted in almost immediate failure of the webbing by melting. The contact force was then reduced to 5 lb in order to reduce the heat generation. Even at this lower load, tests at 80 fps were only run for 30 seconds and tests at 120 fps resulted in almost immediate failure of the specimen by melting. Initially, the same technique used on the 9,000 lb Kevlar webbing was used on this webbing since both are twills with a center reversal. However, when different weave patterns were abraded against one another, one side of the surface would melt while the other remained virtually untouched. This resulted in poor tensile breaks. When similar weave surfaces were abraded against one another, a melting occurred in the center as the photograph in Figure 11 shows. This photograph shows 4 samples abraded at 80 fps with 5 lbs contact force and contact times of 10, 15, 20 and 30 seconds. The leading edges of the samples are aligned on the right hand side of the melt in the photograph showing the increase in contact length at the trailing edge as the test became more severe. The length and width of the melt increased with contact time and the depth remained approximately the same at about 1/2 the thickness of the material as evidence by the exposed filling yarns. This material was re-tested at 120 fps using a contact force of 2.5 lb and at 40 fps using a contact force of 15 lb. Tests also performed at 20 fps and 20 lb contact force resulted in no strength loss in the material. The results of the testing are presented in Figure 12. Strength loss was only found in samples which melted during abrasion. The plot corresponding to testing at 40 fps demonstrated this. No melting in the samples was seen until contact times of more than 15 seconds were used. This initial time period served to heat the sample to temperatures near melting at which time a melt began to appear in the center of the sample. Strength loss and melt width increased proportionately with contact time after the onset of melting, as the testing at 80 fps also indicated.

The energy input associated with abrasion at 120 fps was high enough to cause immediate surface melting with little time for the conduction of heat throughout the sample. Melting at this speed occurred over a broader width than at lower speeds. The backside of the abraded area wrinkled severely as melting occurred. It seems likely that the change in slope in this curve

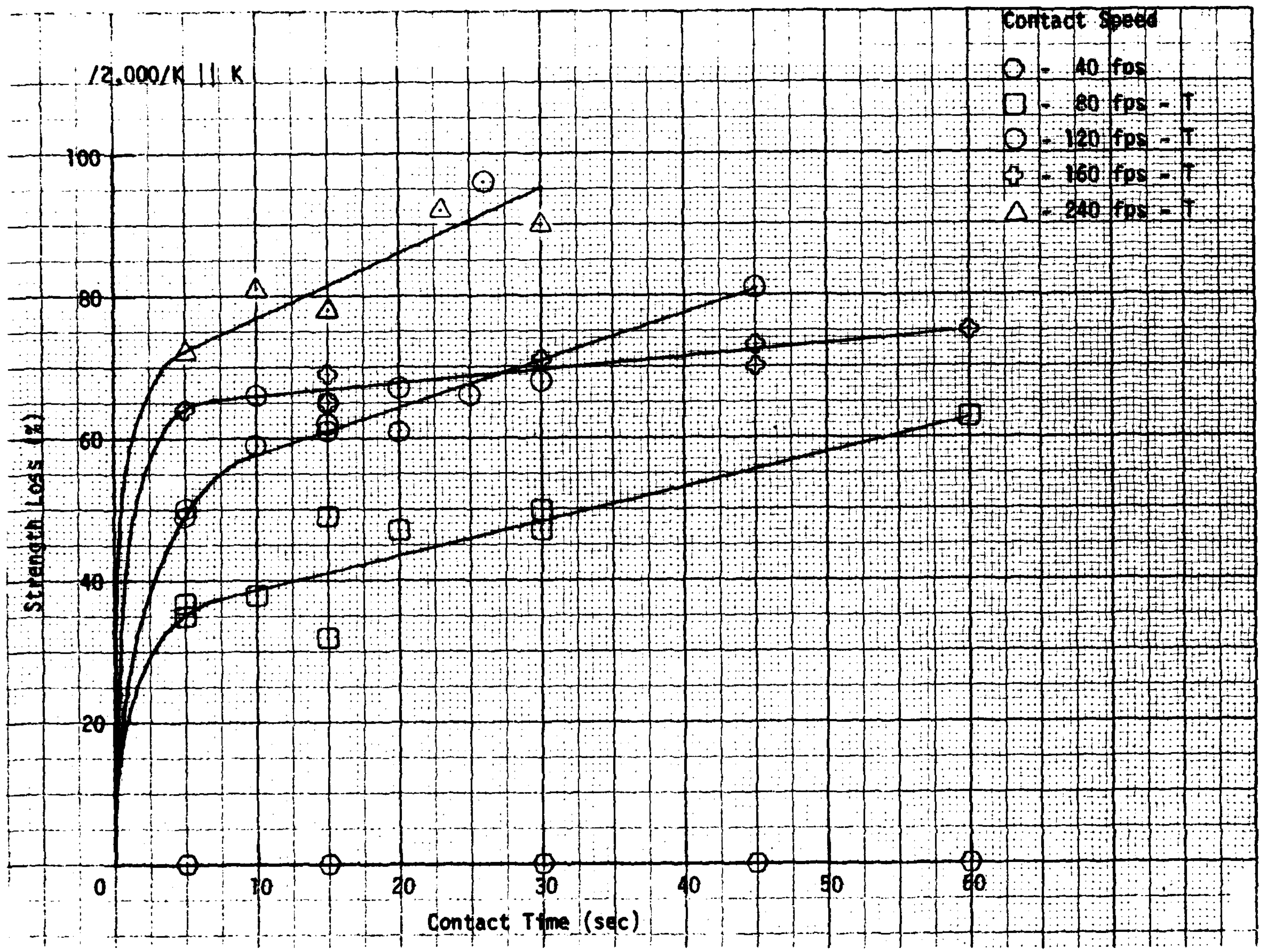
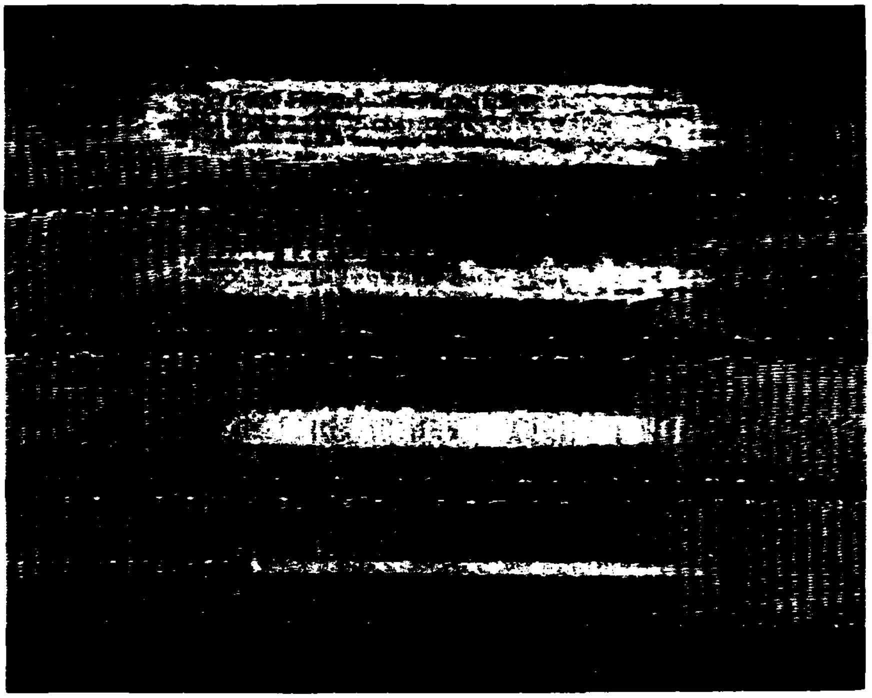


Figure 10. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds



Contact Time (sec)

30

20

15

10

Figure 11. Photograph of Four Specimens of 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Nylon Parallel Configuration at 80 fps with a Contact Force of 5 Lb Showing Increase in Melting with Increase in Contact Time

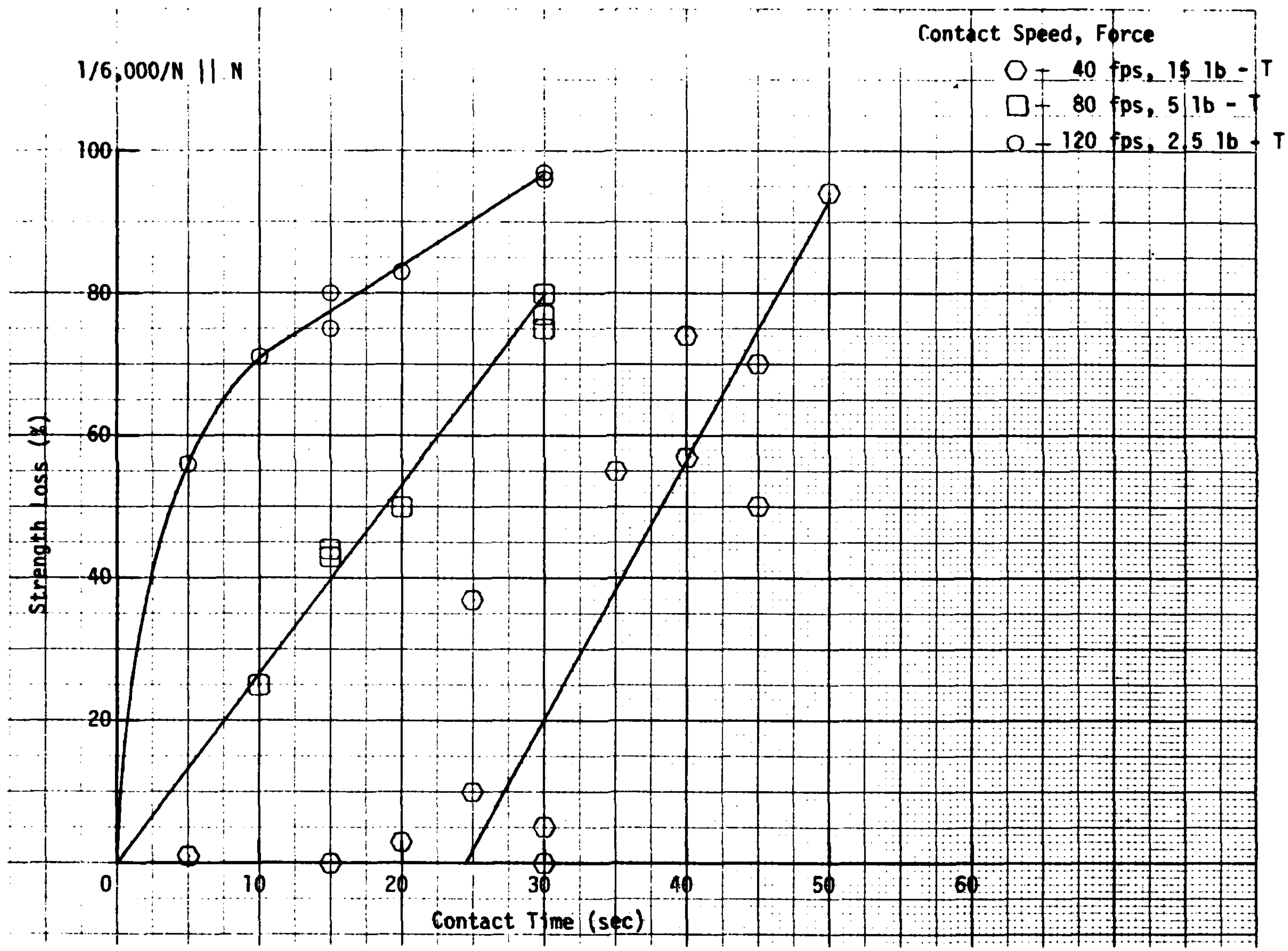


Figure 12. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Nylon Parallel Configuration Using Various Contact Speeds and Forces

indicates a change in the coefficient of friction as the sample melted. In all cases where melting occurred, nylon deposits were evident on the surface of the abrading sample.

The linear relationship between strength loss and contact time was not expected. This may have been due to the nearly instantaneous onset of melting and the linear increase in melt width with contact time. The tensile breaks in this series were poor, generally occurring as a tearing of the specimen. Nylon materials of heavy construction such as this webbing do not usually exhibit breaks of this type. The length differentials in the warp of the abraded sample were evident as a wrinkling of the unabraded surface of the specimen. The melting in the abraded area also bonded warp and filling yarns together, severely inhibiting the mobility of the yarns within the structure. All of this was evidence of the severity of heat generated during abrasion. The initial indication of this testing when compared with that of the 1 inch 6,000 lb Kevlar webbing was that nylon does not withstand heat and abrasion resulting from rubbing at high pressures and speeds as well as Kevlar. The effect of test speed was much greater for the nylon webbing than the Kevlar. Maximum speed for testing of nylon was 120 fps compared to 240 fps for Kevlar. Even at this lower speed, loading conditions were much milder for nylon than Kevlar. The fact that loading conditions had to be varied with test speed in order to get results, shows the extremely large effect of speed on the melting and therefore strength loss of the nylon material.

F. 2,000 Lb Nylon Braid

Testing of the nylon braid proved to be very difficult. As with the nylon webbing, no strength loss was recorded until the onset of melting. It was therefore necessary to match the proper contact force with the contact speed to cause a melting which would result in a strength loss without immediate rupture of the sample. This proved to be more sensitive in the braid than the webbing because of the smaller contact area. There were other problems, peculiar to braids, which further complicated the problem. The double wrap on the wheel resulted in two areas of contact side by side on the surface and edges of the abraded specimen. Every yarn in the structure was exposed within each of the two contact areas. A slight imbalance in the contact force resulted in the onset of melting in one area without significantly damaging the other contact area. After this occurred, the pressure imbalance was further magnified by a shifting of the sample as molten material was removed and a twisting of the sample as the balance of the structure was lost when yarns became completely severed. This type of test resulted in nearly a 100% strength loss only a few seconds after the onset of melting. The time to the onset of melting depended entirely upon test conditions and varied greatly with the magnitude of the load imbalance. The net result, as Figure 13 demonstrates, was a high variation in test results. The effect of loading is also demonstrated in Figure 13 which shows tests performed at 80 fps and loads of 1 and 2.5 lbs. Samples abraded using 1 lb contact force generally showed no visible damage and essentially no strength loss was recorded. Samples abraded using a 2.5 lb contact force exhibited almost immediate melting and strength loss approaching 100%. The third curve shown in Figure 13 represents testing performed at a speed of 40 fps and a load of 5 lb. This plot is similar to the 40 fps plot shown in Figure 12 for the 1 inch 6,000 lb nylon webbing. The plots are similar in that no strength loss

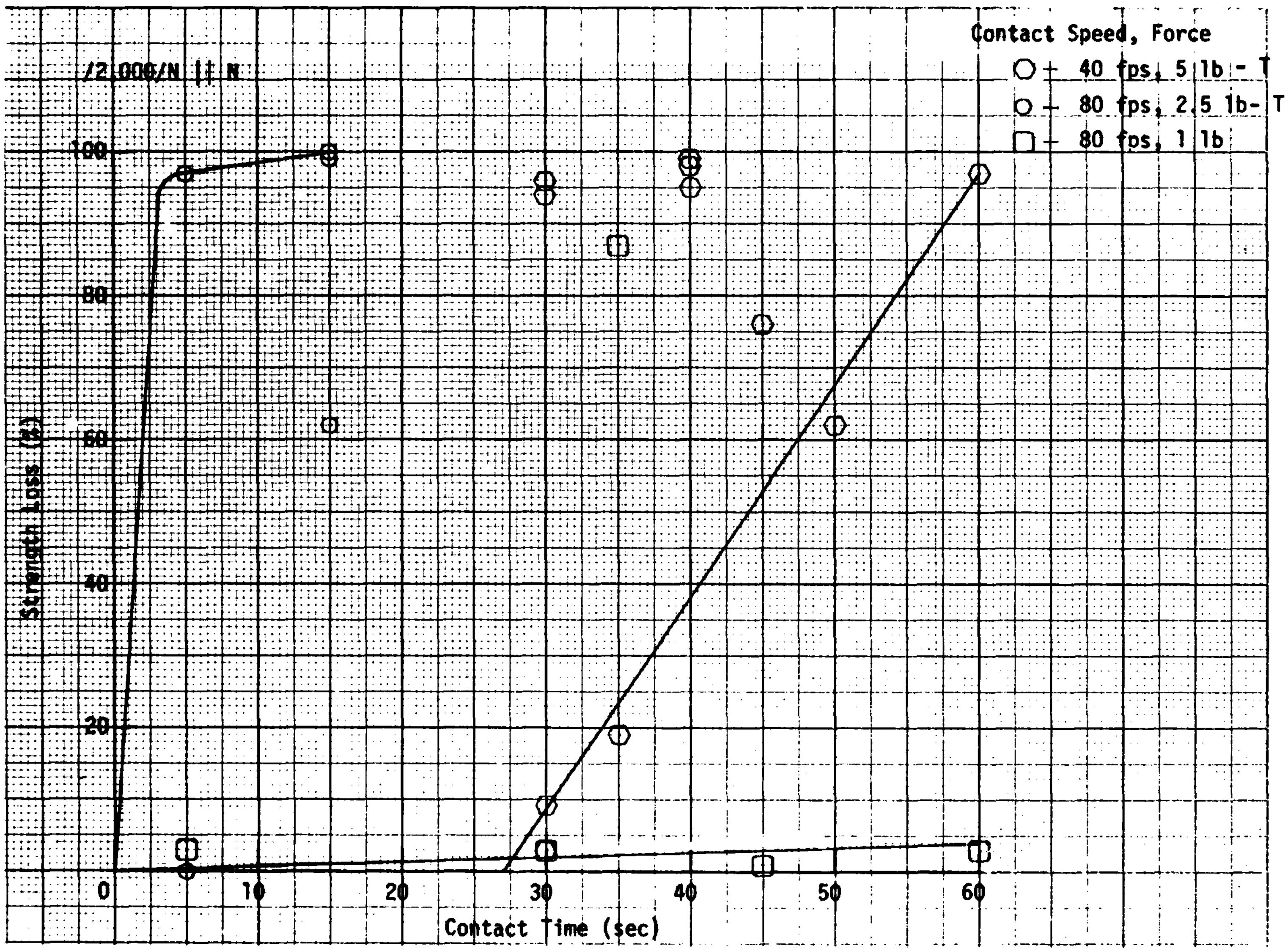


Figure 13. Strength Loss as a Function of Contact Time for a 2,000 Lb Nylon Braid Abraded in the Nylon on Nylon Parallel Configuration Using Various Contact Speeds and Forces

was recorded until melting had occurred after some period of heat generation. After the onset of melting, both curves exhibit linearity and similar slopes although variability in this region does cast some doubt upon the shapes of these curves.

Here again the effect of test speed on the strength loss of nylon materials appeared very large. Abrasion was limited to 80 fps with this nylon braid. Contact loading had to be varied with contact speed in order to generate strength losses within reasonable contact times. In addition to this, sensitivity to conditions affected variability of results substantially raising serious doubt about the abrasion resistance of nylon at high speeds.

G. Kevlar/Nylon Comparison

A comparison between Kevlar and nylon for pure abrasion resistance in the parallel configuration was impossible due to thermal effects. Thermal effects in the form of scorching and melting generally contributed more to strength losses than fiber breakage. Because of thermal effects, it proved to be impossible to abrade the 6,000 lb nylon webbing under the same conditions which were used for the Kevlar webbings. Therefore, one test was run using the 9,000 lb Kevlar webbing abraded at a speed of 120 fps using a contact force of 2.5 lb in order to duplicate the test conditions used for the 6,000 lb nylon webbing. The 9,000 lb Kevlar webbing was used instead of the 6,000 lb Kevlar webbing because it more closely resembled the nylon webbing in construction, weight, thickness and surface characteristics. The test was run continuously for 5 minutes. The abraded specimen showed no signs of scorching or fiber breakage and when tensile tested did not even fail in the abraded area. This result was expected based on the results of testing performed at the various conditions reported previously.

A comparison between Kevlar and nylon braids was possible from the data gathered in parallel abrasion testing. Both braids were tested at a speed of 40 fps using a contact force of 5 lb. The Kevlar braid sustained no loss in strength in tests conducted using up to 60 seconds contact time. Tensile breaks on these specimens did not even occur in the abraded area. The nylon braid sustained no strength loss until the onset of melting after approximately 25 seconds of contact time. At 30 seconds, however, strength losses ranging from 2 to 95% were found because of melt sensitivity and the test configuration as described previously. However, the general rate of abrasion (or melting) beyond 30 seconds was quite high even when the tests could be conducted properly. Tests performed at 80 fps and 5 lb contact force with the Kevlar braid yielded a maximum strength loss of 60% at 60 seconds contact time. The nylon braid however sustained over 95% strength loss in 5 seconds when tested at 80 fps with a contact force of 2.5 lb. Based on tests conducted at 80 fps using 1 and 2.5 lb contact force shown in Figure 13, testing of the nylon braid at 80 fps with a contact of 5 lb would have resulted in immediate failure of the specimen. The superior performance of the Kevlar braid in this testing is further amplified by the higher contact pressures used in testing it due to the difference in contact area determined by the relative sizes of the two braids.

H. Strength Loss Mechanisms and the Effect of Test Parameters in Kevlar and Nylon

Three strength loss mechanisms were found in this testing. The first was piling. Changing contact length, and therefore specimen tension, enabled us to avoid this mechanism during the testing. The second strength loss mechanism was fiber breakage. In some cases this was the most significant mechanism present. The third strength loss mechanism was scorching and melting due to heat generation. This proved to be the major contributor to strength loss in most of the testing and the only important mechanism for strength loss in the nylon testing. This view was also held by Swallow and Webb[7] who stated that in high speed abrasion "these factors (thermal effects) largely control the mechanism of abrasion of nylon on nylon". In general, strength loss caused by all mechanisms increased with increasing contact force, speed and time. The Kevlar materials generally sustained high strength losses in the first few seconds of contact after which the rate of abrasion decreased rapidly usually becoming linear and sometimes decreasing to near zero as the test proceeded. In general, specimens abraded under similar conditions (specimen tension and contact force) yielded similar relationships between strength loss and contact time when abraded at different speeds. The apparent result of increasing specimen tension (by decreasing deflection when a greater wheel radius was used) in Kevlar materials was to decrease abrasion, often to the point where abrasion at a lower tension and speed would result in strength losses which were equal to or greater than strength losses at higher speeds and tensions. The effect of test speed was generally much greater for nylon materials than Kevlar, as was variability of results. These effects and the need for the use of milder test conditions were attributed to the low melting point of nylon and the dependence of heat generation on test speed and contact force. The migration of molten nylon from the abraded to the abrading specimen exposing new nylon fibers resulted in linear rates of strength loss in some cases. The scorching and glazing of Kevlar fibers which did not break away seemed to cause a drastic reduction in the coefficient of friction leading to a balance between heat generation and heat loss. This sometimes resulted in a rate of strength loss which approached zero or perhaps a net rate of heat generation which remained constant in the latter part of the tests. Although much of this theory is conjecture, it is based on observation of a large number of tests and supported by the figures presented here. This data shows conclusively that the high speed abrasion resistance of Kevlar abraded in this configuration, and therefore inclusive of thermal effects, far exceeds that of nylon and is inconsistent with its dubiously founded reputation.

SECTION VI

KEVLAR ON KEVLAR (NYLON ON NYLON) PERPENDICULAR ABRASION

A. 1 Inch 6,000 Lb Kevlar Webbing

The 1 inch 6,000 lb webbing was abraded at speeds of 240, 160, 120 and 80 fps in the Kevlar on Kevlar perpendicular configuration. A contact pressure nominally equivalent to the parallel testing value was achieved by decreasing the contact force by the ratio of the contact areas (3:1) resulting in a 5 lb contact force for the perpendicular testing. Figure 14 shows the results of this test series. Table 7 gives individual test results. Scorching was only evident in the specimens abraded at 240 fps. All of the tensile breaks were good clean breaks occurring in the abraded area. The strength loss in this configuration was lower than that found for the parallel configuration even though the contact pressure was nominally equal for the two configurations. This may have been due to the extremely high tension used in the abraded specimen in order to avoid contact between the webbing and the edge of the wheel. In order to avoid bouncing, it was necessary to lower the shoe by a slow release of air pressure as mentioned previously. A block was also machined to fit in the slot on the wheel rim through which the abrading material was normally passed to the two pin clamps. This was necessary to prevent cutting of the abraded webbing on the edges of the slot. These techniques are discussed in Section III of this report.

As in the parallel testing discussed previously, strength losses generally increased with increasing contact time and speed. Except for the 80 fps testing, the rate of abrasion was highest in the initial portion of the curve, decreased with increasing contact time and became somewhat linear at the longer contact times. The initial high strength losses seemed lower than what was seen in the parallel testing. This may have been due to the slow release of the shoe in the perpendicular testing. The similarities between results of testing at 160 and 120 fps may have been due to a higher tension in the abraded webbing in the testing at 160 fps. Changing of the wheels and test set up between these speeds may have resulted in this change in tension even though the contact length did not depend upon the tension in the sample.

B. 1 Inch 9,000 Lb Kevlar Webbing

The 9,000 lb webbing was abraded in this configuration at speeds of 80, 120 and 160 fps using a contact force of 20 lb. This resulted in a contact pressure which was roughly three times that used in the parallel configuration. Figure 15 gives the results of this testing. Testing at 80 fps resulted in no scorching or abrasive damage except for the test conducted at 60 seconds contact time. This was the only specimen which failed in the abraded area when tensile tested. All of the other specimens in this series failed at the point of initial contact with the jaw, which is typical of a control test. Testing at 120 and 160 fps did result in severe scorching and abrasive damage. Tensile breaks of these webbings were generally poor, usually occurring as a tear initiated at the leading edge of the sample.

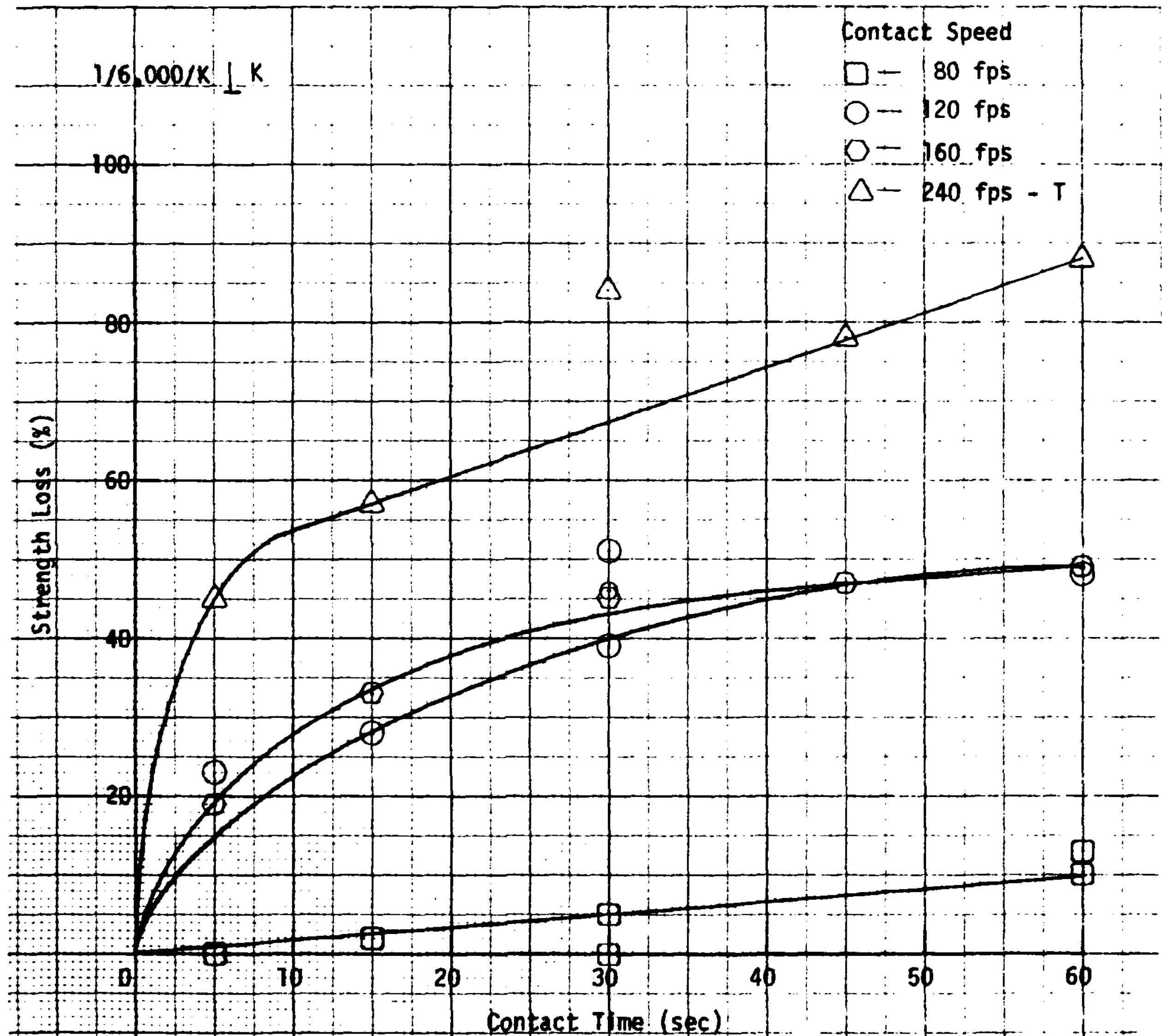


Figure 14. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Perpendicular Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

TABLE 7

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON ON NYLON) PERPENDICULAR CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	5	80	5,790		0		2			0 5					10 13[1]
	5	120	6,008		23		28 28			39 51					48
	5	160	6,045		19		33			45			47		60
	5	240	6,045		45		57			84 46			78		88
1 inch 9,000 lb Kevlar Webbing	20	80	10,560		3		3			2			2		14
	20	120	9,900		39 74[6]	83 73 62	71 78	76	82	96					
	20	160	10,140		66 88[6]	77	76 70	83	96						
2,000 lb Kevlar Braid	10	20	2,200		3	7				30	85[2]	85[2] 83[2]			
	5	40	2,200		22[5] 18	36[6] 52	55[7] 67	83[2]	63[2]	89[2]					
	1	80	2,200		20[3]	29[3]	20	27 24[2]	37[3]	46			60		20[2] 56[2] 62[2,4]
	1	120	2,370		34[5] 38	54[6] 41 68[2]	81[2]	89[2]							

TABLE 7 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON ON NYLON) PERPENDICULAR CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds)											
				3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Nylon Webbing	20	40	6,680												0
	5	80	6,680		16		75		100	13			96		
							74			87			94		
							73								
							69								
							61								
	2.5	120	6,680		18	10	94	37	87	86					
							39			91					
							89								
2,000 lb Nylon Braid	10	20	2,450		2		4		31	31	39	98[1]			
													95		
	2.5	40	2,450				2	9		9			13		37
														7[1]	
	1	80	2,450	100											

1. Control value 6,010 pounds.
2. Control value 2,250 pounds.
3. Control value 2,370 pounds.
4. Contact time 55 seconds.
5. Contact time 3 seconds.
6. Contact time 7 seconds.
7. Contact time 12 seconds.

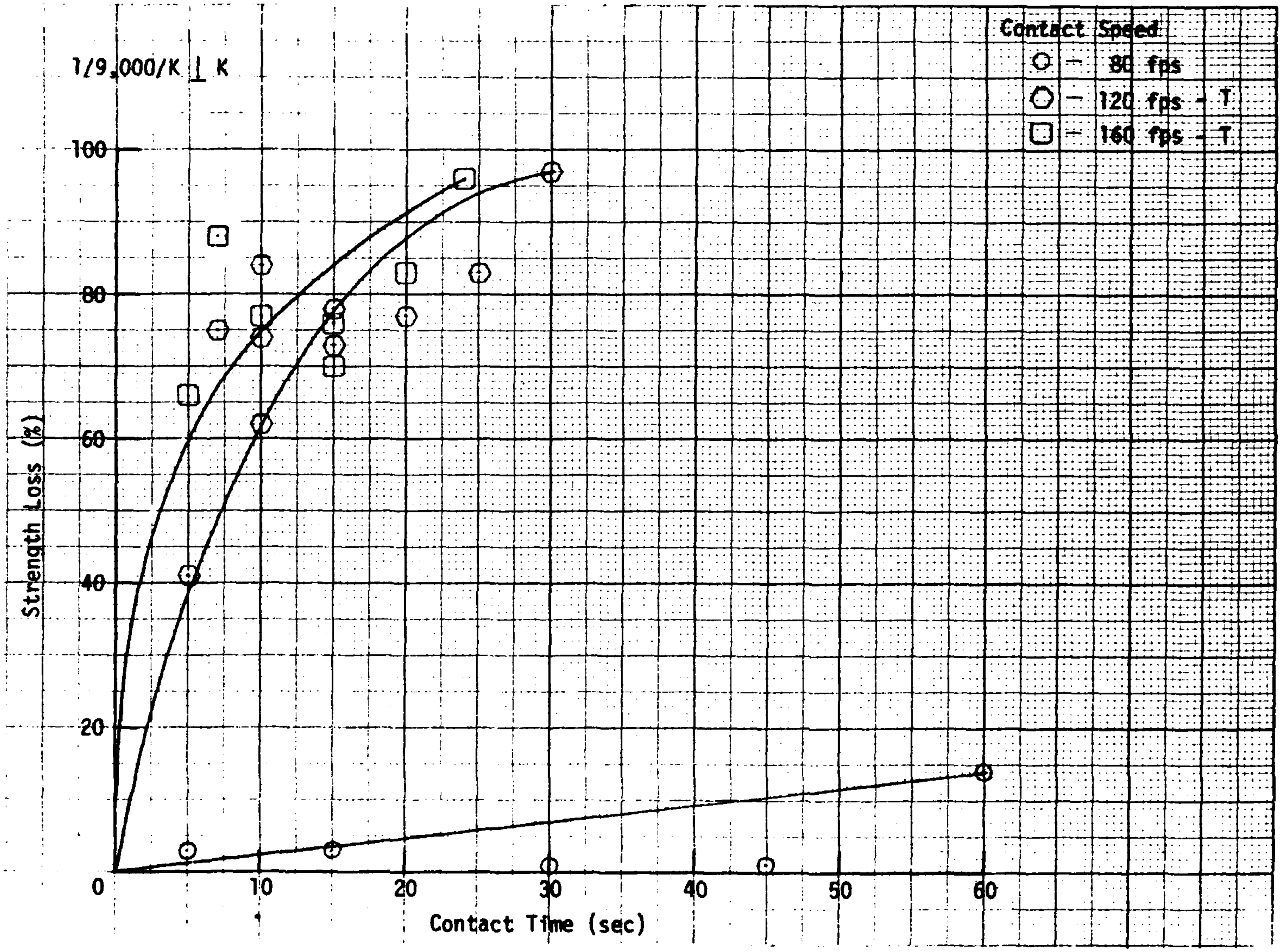


Figure 15. Strength Loss as a Function of Contact Time for a 1 Inch 9,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Perpendicular Configuration Using a Contact Force of 20 Lb and Various Contact Speeds

The shape of the curves representing abrasion at 120 and 160 fps is similar to what has been seen so far. High strength losses were seen in a short time. The strength loss beyond this initial time period occurred much more slowly. The variability of results was high in this testing which resulted in difficulty defining curve shapes. Severe scorching and glazing of the sample occurred in a very short time (under 5 seconds). After this initial scorching, only minor increases in scorching were evident with increasing contact time. The change in the surface of the specimen after scorching most likely reduced the heat generation. The further loss in strength may have occurred as scorched fibers broke away exposing inner fibers to be heated and/or abraded. The similarities between results at 160 and 120 fps again seemed due to a change in tension as was suspected in the testing of the 1 inch 6,000 lb Kevlar webbing.

C. 2,000 Lb Kevlar Braid

Figure 16 shows the results of testing of the braid in this configuration at speeds of 20, 40, 80 and 120 fps. Because of the small contact area, this material was very sensitive to contact force. It was therefore necessary to use three different loadings with the four different speeds. Testing at speeds of 80 and 120 fps was performed using a contact force of 1 lb. Testing at 20 and 40 fps was performed using contact forces of 10 and 5 lb respectively. All of the curves in Figure 16 exhibit linear relationships in the initial portion of the curves, however, variability in the data, especially at short contact times, casts some doubt upon the shape of these curves. Only the curve corresponding to testing performed at 20 fps remained linear through its entire length. This was most likely due to the high contact force used in this testing. Abrasion of the braid in this configuration presented many problems. Because of the small contact area, less than half of the yarns in the structure were being abraded. After the abraded yarns were severed, the balanced nature of the braid structure was lost. This drastically lowered the tension in the sample, changed the geometry of the test configuration, and caused contact between the abraded sample and the wheel. Tensile breaks in this series were generally good; however, some samples left 1 or 2 yarns intact after the remaining yarns had ruptured.

Most of the abraded samples exhibited some form of scorching. However, some of this scorching was different in that it was lighter in color than usual and very glazed*. This type of scorching was most evident in the samples abraded at 20 and 40 fps. Close examination of the abraded area revealed that the fibers were bonded together indicating that melting had occurred and that the glazing was a smearing of molten Kevlar. Discussions with the Project Engineer have revealed that this same type of light brown glazing has been seen in braids taken from actual drop test parachutes.

D. 1 Inch 6,000 Lb Nylon Webbing

The 6,000 lb nylon webbing was abraded in the perpendicular configuration at speeds of 40, 80 and 120 fps. Figure 17 shows the results of this testing. It was necessary to use a different contact force for each test speed because of the low melt temperature of nylon. Tests performed at a

*See also Section X, page 127.

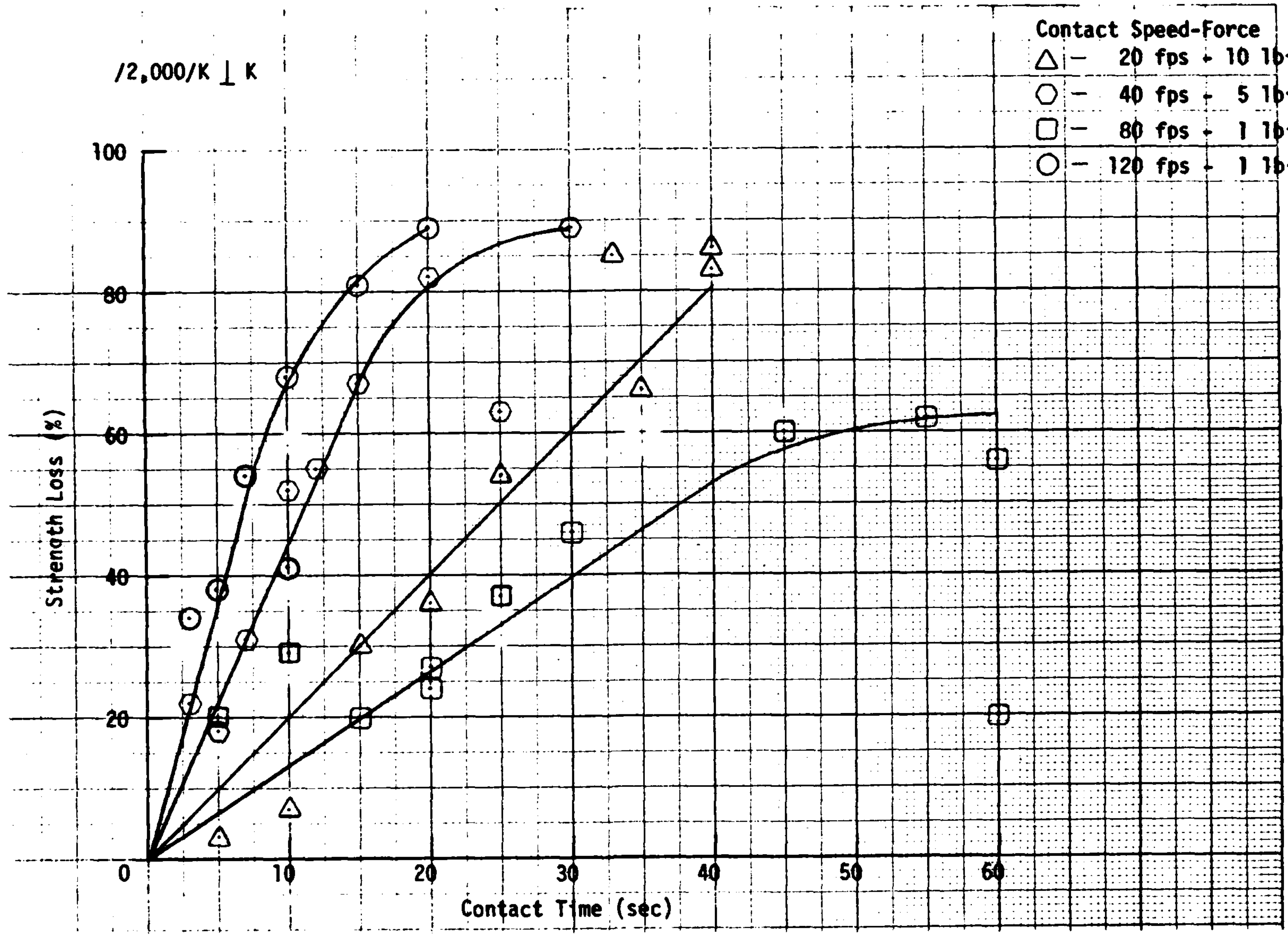


Figure 16. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Kevlar Perpendicular Configuration Using Various Contact Speeds and Forces

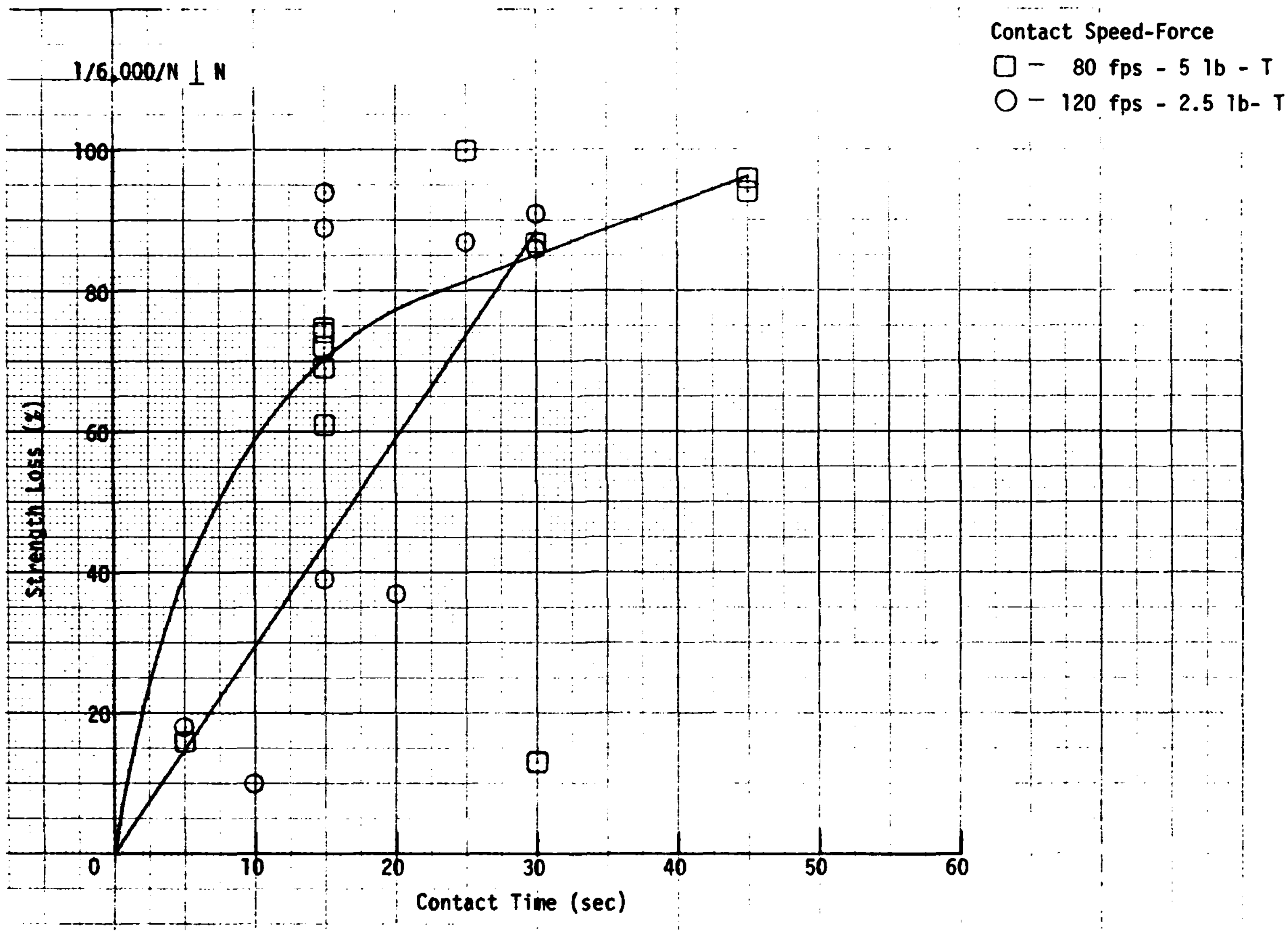


Figure 17. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Nylon Perpendicular Configuration Using Various Contact Speeds and Forces

speed of 40 fps using a 20 lb contact force showed no strength loss or melting. Samples abraded at 80 fps with a 5 lb contact force exhibited severe melting and generally poor tensile breaks as did samples abraded at 120 fps with a contact force of 2.5 lb. Variability of results was high. This may have been due to the sensitivity of the material to melting and therefore the conditions which initiated it. Also, the change in the material and test configuration caused by the onset of melting often produced uneven melt, which resulted in poor tensile breaks. In general, the normal relationships between strength loss and contact time applied in this testing as they have in previous testing. However, exact definition of these relationships was impossible due to variability in results. Comparison between these curves is not good since they involve the use of two different test speeds and contact forces.

E. 2,000 Lb Nylon Braid

The nylon braid was abraded at speeds of 20, 40 and 80 fps. Tests performed at 80 fps using a contact force of 1 lb resulted in immediate failure of the braid by melting. Tests performed at 40 fps with a contact force of 2.5 lb showed significant strength loss after the onset of melting as did samples abraded at 20 fps using a 10 lb contact force. Tensile breaks and variability of results in this series were generally good as Figure 18 indicates. High strength losses in this testing were attributed to severe melting and bonding of intact yarns restricting yarn mobility within the structure. The curves in Figure 18 show this increasing melt and bonding as an increasing slope (increasng rate of abrasion) with increasing contact time. This type of curve has not been seen before in any testing, but seems to be explainable in terms of small contact area and bonding of yarns not being abraded. Again, a comparison between these two curves is not meaningful since both speed and contact force were varied.

F. Kevlar/Nylon Comparison

Comparison of Kevlar to nylon was limited in this test series*. The 6,000 lb nylon and Kevlar webbings were abraded at 80 fps with a 5 lb contact force. Comparison of these results (Figures 17 and 14) shows the obvious superior performance of the Kevlar webbing. The 9,000 lb Kevlar webbing (Figure 15) was abraded with a 20 lb contact force and its performance at 80 fps was similar to that of the 6,000 lb Kevlar webbing at 80 fps (and 5 lb contact force), and far superior to that of the nylon webbing.

Both of the braids were abraded at a speed of 20 fps using a contact force of 10 lb. Comparison of Figures 16 and 18 shows the marginally better performance of the nylon braid. The major difference in performance came in the initial portion of the curve where the rate of abrasion for the nylon braid was low. However, the nylon braid is approximately twice the size of the Kevlar braid and therefore the ratio of contact areas between the two is 4 to 1. This makes a comparison between the two braids less than ideal since contact pressure depends upon contact area for a given load.

In order to get a direct comparison between Kevlar and nylon in this test configuration, several tests were run with extended contact times. Both the 1 inch 6,000 and 9,000 lb Kevlar webbings were abraded at 80 and 120 fps using contact forces of 5 and 2.5 lb respectively. All tests were run for 5 minutes at these conditions. Table 8 gives the results of this testing along with some results taken from Table 5 for the testing of the 1 inch

*See also Section XI, page 134.

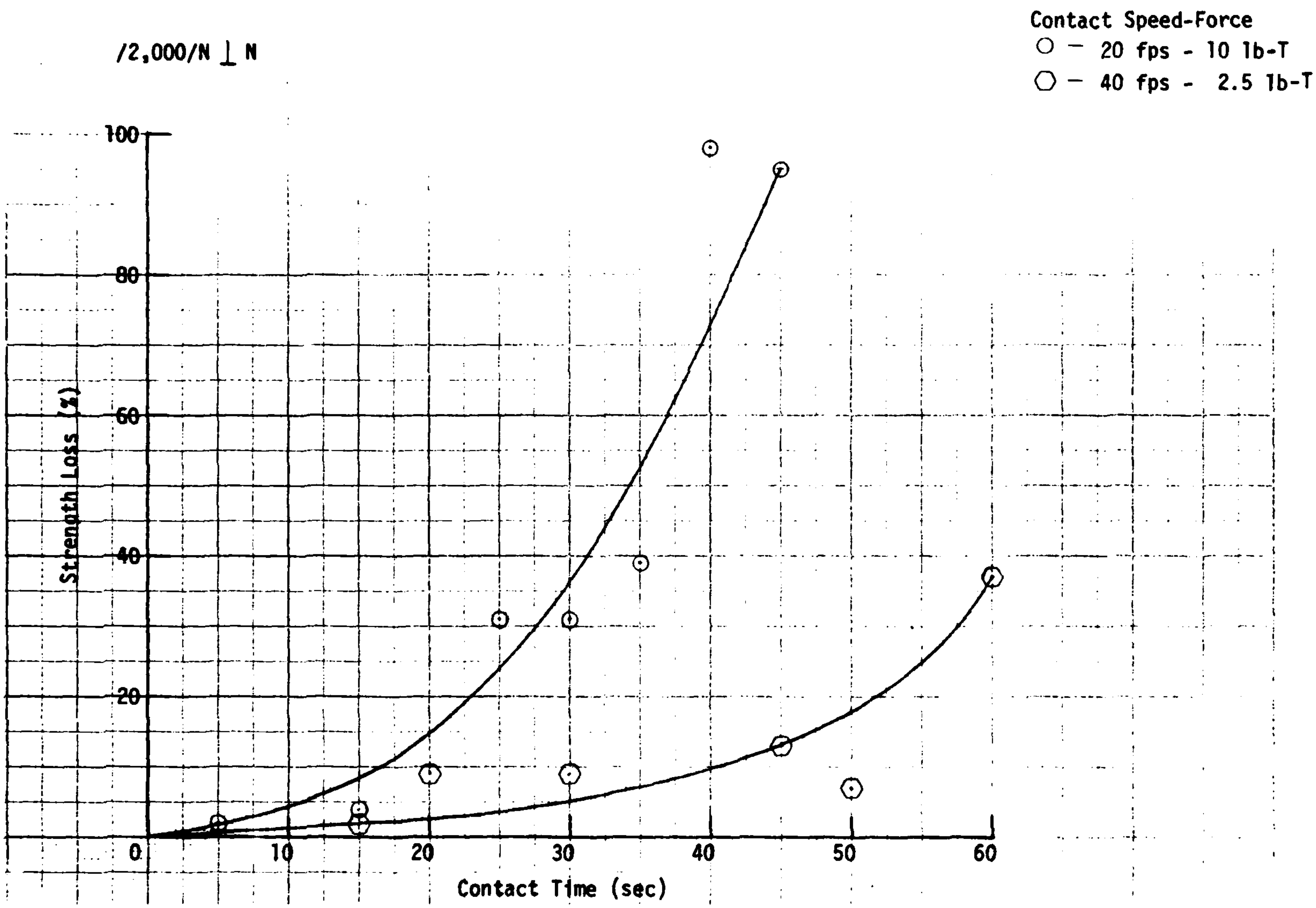


Figure 18. Strength Loss as a Function of Contact Time for a 2,000 Lb Nylon Braid Abraded in the Nylon on Nylon Perpendicular Configuration Using Various Contact Speeds and Forces

6,000 lb nylon webbing abraded at the same conditions. As Table 6 indicates, only the 6,000 lb Kevlar webbing abraded at 120 fps showed any significant strength loss in the extended contact time tests. However, the 1 inch 6,000 lb nylon webbing was almost totally destroyed in less than 60 seconds when abraded at the same conditions. As has been mentioned in previous sections, this test configuration may not be optimum for direct comparison of pure abrasion resistance between Kevlar and nylon because of heat effects. However, if sample heating due to friction when rubbed is considered to be as viable a strength loss mechanism as pure abrasion due to rubbing, then this comparison shows far superior performance by the Kevlar material than the nylon.

TABLE 8

COMPARISON OF THREE WEBBINGS ABRADED UNDER IDENTICAL CONDITIONS IN THE KEVLAR ON KEVLAR (NYLON ON NYLON) PERPENDICULAR CONFIGURATION

Material	Contact Force (lb)	Contact Speed (fps)	Control Value (lb)	Contact Time	Strength Loss (%)
1 inch 6,000 lb	5	80	6,679	45 seconds	96
Nylon webbing				45 seconds	94
herringbone twill					
weave	2.5	120	6,679	30 seconds	86
				30 seconds	91
1 inch 6,000 lb	5	80	6,164	5 minutes	69
Kevlar webbing					
plain weave	2.5	120	6,164	5 minutes	8
1 inch 9,000 lb	5	80	10,125	5 minutes	8
Kevlar webbing					
herringbone twill	2.5	120	10,125	5 minutes	8
weave					

SECTION VII

KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL ABRASION

The material which was selected to simulate concrete was Norton E-Z flex metalite cloth Closekote abrasive with a 400J grit. This material is a fabric backed abrasive purchased in 2 inch wide x 50 yd rolls. It was chosen because it was suitable for the test procedure being used, not because its surface matched the surface of a concrete runway. It seemed an ideal material for examining the resistance of these structures to rubbing on a nonfibrous abrasive surface.

In general, the testing in this configuration proceeded very smoothly. The Kevlar materials did not generally exhibit scorching, either because of light contact loads used or because of the migration of broken Kevlar fibers from the abraded area. After abrasion testing, the abrasive was filled with broken fibers. For whatever reason, the testing of Kevlar in this configuration seemed to be lacking of any temperature effects. The abraded area generally exhibited uniform and consistent wear. This resulted in a minimization of both the need for retesting and variability of results. The lack of temperature effects indicated that this abrasion configuration would be better for comparison between Kevlar and nylon than the Kevlar on Kevlar (nylon on nylon) configuration. However, the nylon materials again tended to be susceptible to heat effects and melting. Some of the milder abrasion conditions did result in pure abrasion without melting. These conditions would probably be optimum for comparison of abrasion resistance between Kevlar and nylon. Table 9 presents individual test results for this testing.

A. 1 Inch 6,000 Lb Kevlar Webbing

This material was abraded in this configuration at speeds of 20, 40, 80 and 120 fps using a contact force of 5 lb. Some preliminary testing was also performed at 80 fps using a contact force of 2.5 lb. Figures 19 and 20 show the results of this testing. Overall variation in test results was very good. Most of the tensile breaks were good; however, there were some poor breaks. The curves in Figures 19 and 20 exhibit similar shapes. All of the curves have a maximum slope in the initial portion of the curve indicating a maximum rate of abrasion at the beginning of the test. The decrease in slope to near zero at 60 seconds indicated a probable loss in abrasive power of the abrasive strip. This was most likely due to the migration of broken Kevlar fibers from the abraded surface to the abrasive material. These became imbedded in the abrasive and smoothed the surface. This change in slope may also have been due in part to an increase in contact area as the fabric knuckles (which are very pronounced in this particular construction) wore down. This would have caused a decrease in the contact pressure as the test proceeded. There is a greater effect of contact force than speed on the strength loss. Speed effects in this testing appear similar to those found in the parallel on Kevlar testing of this material (Figure 6).

TABLE 9

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	5	20	6,160		30		33			41			46		39
	5	40	6,160		31[1]		42[1]			57			62		76
	5	80	6,010		48		69			90			96		98
							69						95		
	5	120	6,010		66	75	87	90		97					
							86								
	2.5	80	6,010		31		34			42					52
							42			45					
1 inch 9,000 lb Kevlar Webbing	5	40	9,900				30			30			28		33
	5	80	10,560		26		36			43					65
							38			41					60
	5	120	10,560		38		48			55					85
							44			56					
	5	160	10,140		48		71			86			89		93
	5	240	10,140		67		80			88		91			93

TABLE 9 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
2,000 lb Kevlar Braid	5	20	2,230		6		24			19			15		19
	5	40	2,230		18		37			44			47		41
	5	80	2,150		30		45			46			65		67
	5	120	2,150		64		80	80		94					
1-3/4 inch 4,000 lb Kevlar Webbing	1	20	4,170		38		45			52			56		65
	1	40	4,170		40		57			64			70		75
	1	80	4,170		53		66			78			84		88
	1	120	4,170		69	73	77	86		93					
2 inch 1,000 lb Kevlar Ribbon	1	20	880		93		98			98			100		100
	1	40	880			98	99		99	100	100				
2 inch 480 lb Kevlar Ribbon	1	20	448		14[5] 6 9	5[2] 17[2] 62	94	90	100						

TABLE 9 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Nylon Webbing	5	20	6,900		34		46			57			60		72
	5	40	6,690		54		66			87			93		96[3]
	5	80	6,690		81 92	87 89	92			96					
	5	120	6,690	95	98	100[4]									
	2.5	80	6,690		55		85 61 43 78			66 84					96 98
2,000 lb Nylon Braid	5	20	2,450		31		59			78			90 95		
	5	40	2,460		97	98	98			100					
	5	80	2,460		100										

TABLE 9 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
2 inch 1,000 lb Nylon Ribbon	1	20	1,150		25		33			43			46		51
	1	40	1,150		30		47			65			67		84
	1	80	1,150		54 33		77 52			81			87		91
	1	120	1,150		62		90			99 99					
2 inch 460 lb Nylon Ribbon	1	20	498		72		83			91			91		94
	1	40	498		84		90			96			95		96
	1	80	498		90	93	94	100							

1. Control value 6,010 pounds.
2. Contact time 7 seconds.
3. Control value 6,900 pounds.
4. Contact time 8 seconds.

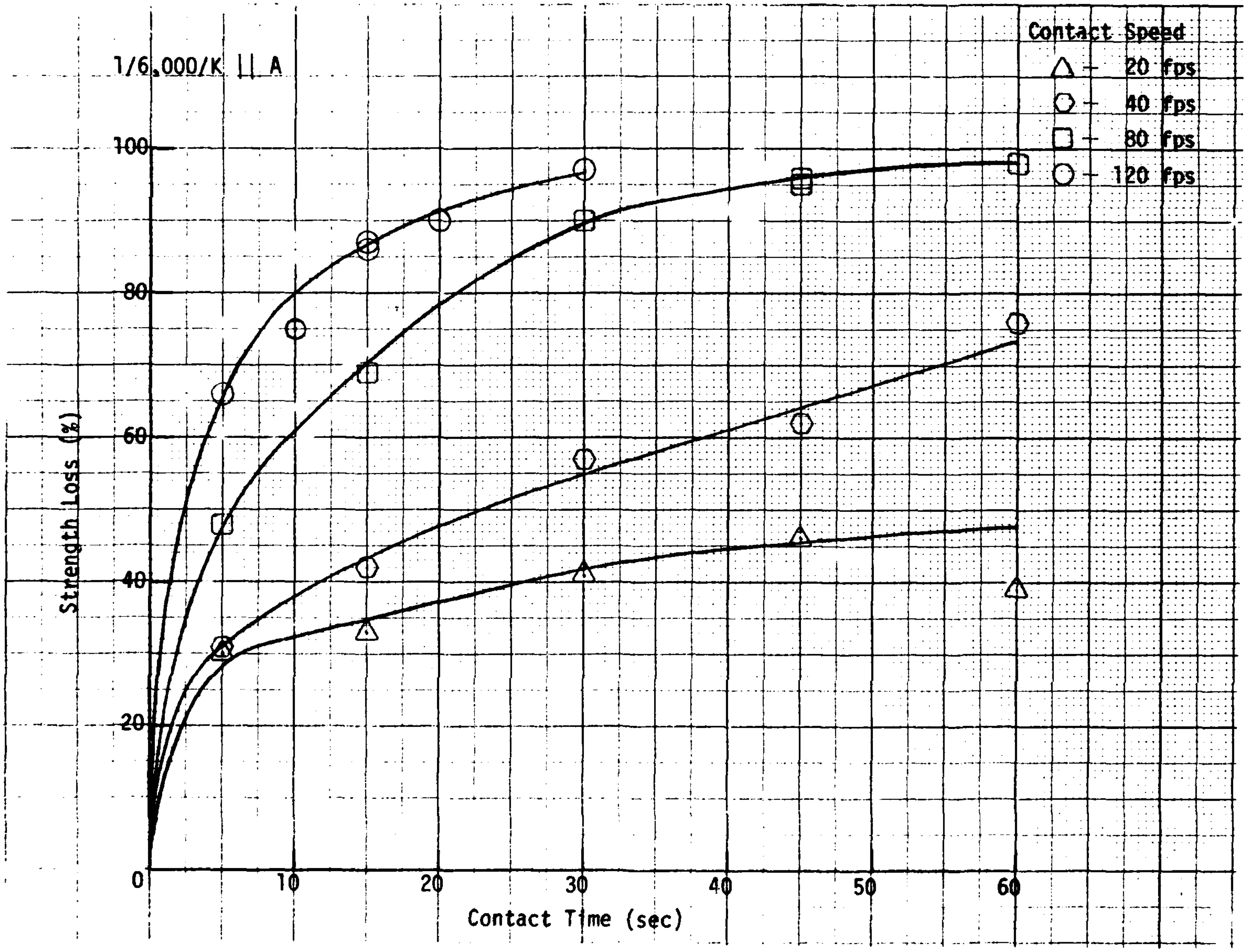


Figure 19. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

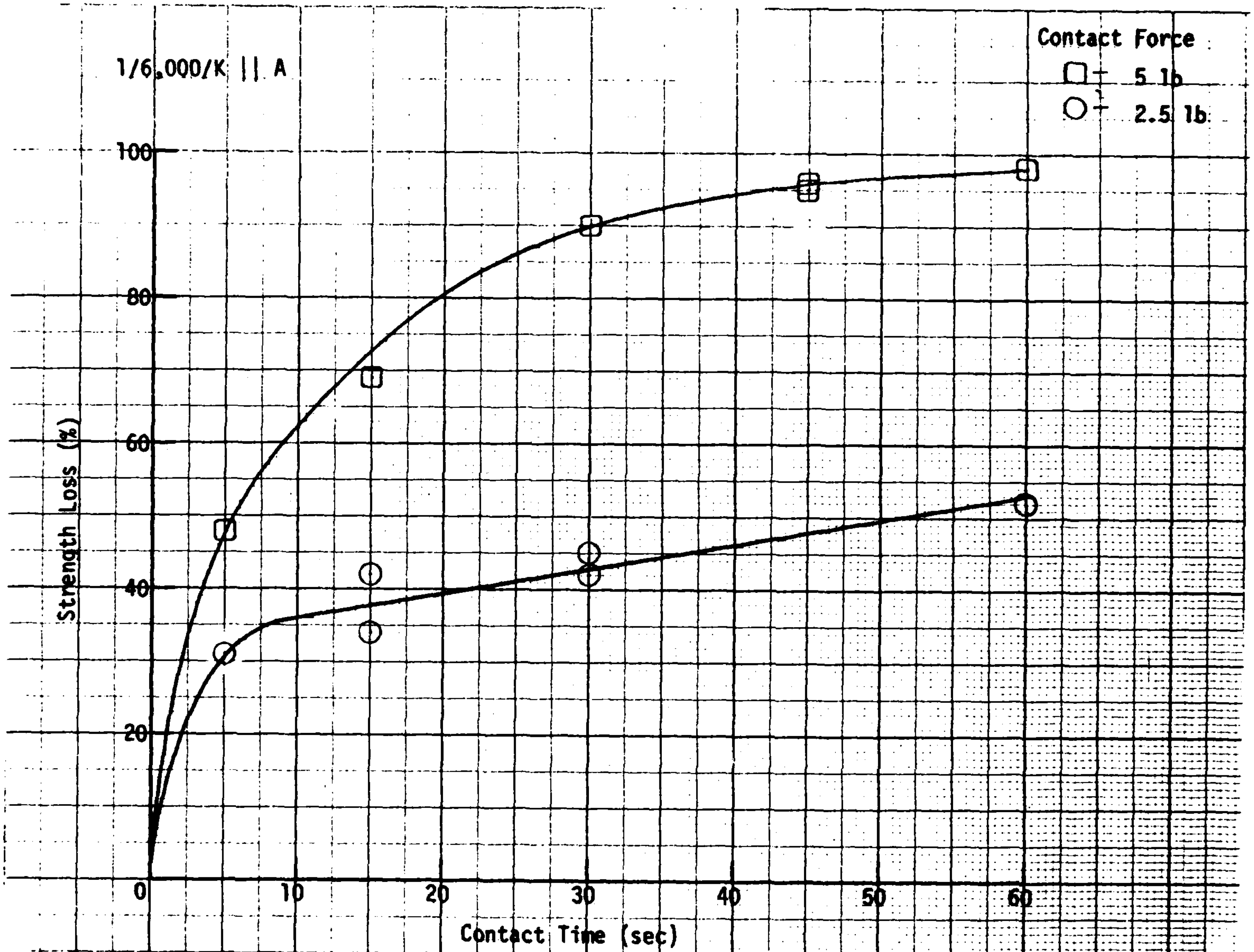


Figure 20. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 80 fps Using Two Different Contact Forces

B. 1 Inch 9,000 Lb Kevlar Webbing

This material was abraded in this configuration at speeds of 40, 80, 120, 160 and 240 fps using a contact force of 5 lb. This material was not originally scheduled for abrasion on an abrasive surface, as outlined by the Statement of Work. However, similarities in structure between this webbing and the 1 inch 6,000 lb nylon webbing led to abrasion in this configuration in order to compare abrasion resistance of similar constructions under conditions where temperature effects could be kept to a minimum. Figure 21 presents the results of testing of the 1 inch 9,000 lb Kevlar webbing. The maximum slope of the curves occurs again in the initial part of the test. However, the curves for the slower speeds become linear after this initial portion up to the maximum contact time of 60 seconds. This seemed to indicate that the surfaces of both the abraded specimen and abrasive strip had reached an equilibrium state. This could have resulted in the constant rate of abrasion which was seen here but not in the testing of the 1 inch 6,000 lb webbing.

The tensile breaks in this series were generally good except for testing at the two highest speeds where the specimens tended to tear. Scorching and glazing was evident only in specimens abraded at 240 fps. Specimen glazing at 240 fps reduced the coefficient of friction and therefore rate of abrasion to produce the convergence of the 240 and 160 fps curves at 60 seconds contact time. Unlike the Kevlar on Kevlar testing, the increase in tension in the abraded sample due to a change in wheel diameter (120 to 160 fps) did not cause a decrease in abrasion. This is evidenced in Figure 21 by the separation between curves corresponding to testing at 160 and 120 fps as opposed to the curves in Figure 9.

C. 2,000 Lb Kevlar Braid

The 2,000 lb braid was also abraded at speeds of 20, 40, 80 and 120 fps using a contact force of 5 lb. Figure 22 shows the results of this testing. Tensile breaks in this series were good. The braid exhibited extremely good abrasion resistance in this configuration when compared to the Kevlar webbings which had a much greater contact area. The contact pressure associated with this testing was high enough to cause scorching at speeds of 80 and 120 fps. This was not the case with either of the Kevlar webbings. Here again, the curves in Figure 22 indicate maximum abrasion at the start of the test. The curves associated with testing at 20, 40 and 80 fps approach zero slope at or before 60 seconds of contact time. The testing at 120 fps was harsh enough to cause a 100% strength loss before 60 seconds contact time.

D. 1 3/4 Inch 4,000 Lb Kevlar Webbing

This material was abraded at speeds of 20, 40 80 and 120 fps using a contact force of 1 lb. Figure 23 shows the results of this testing. The tensile breaks in this series were poor. Most of them occurred as tears or random popping of warp yarns. This was also true of some of the control tests. However, as Figure 23 shows, the variability of results was very low. No scorching was evident in any of the specimens tested. A slow release of the shoe was used in this testing as with all ribbons. As has been the case in all testing thus far, maximum abrasion occurred in the initial part of the test. All of the curves exhibit good parallelism and decreasing slope with increasing contact time. Strength losses in this series were high considering the mild test conditions.

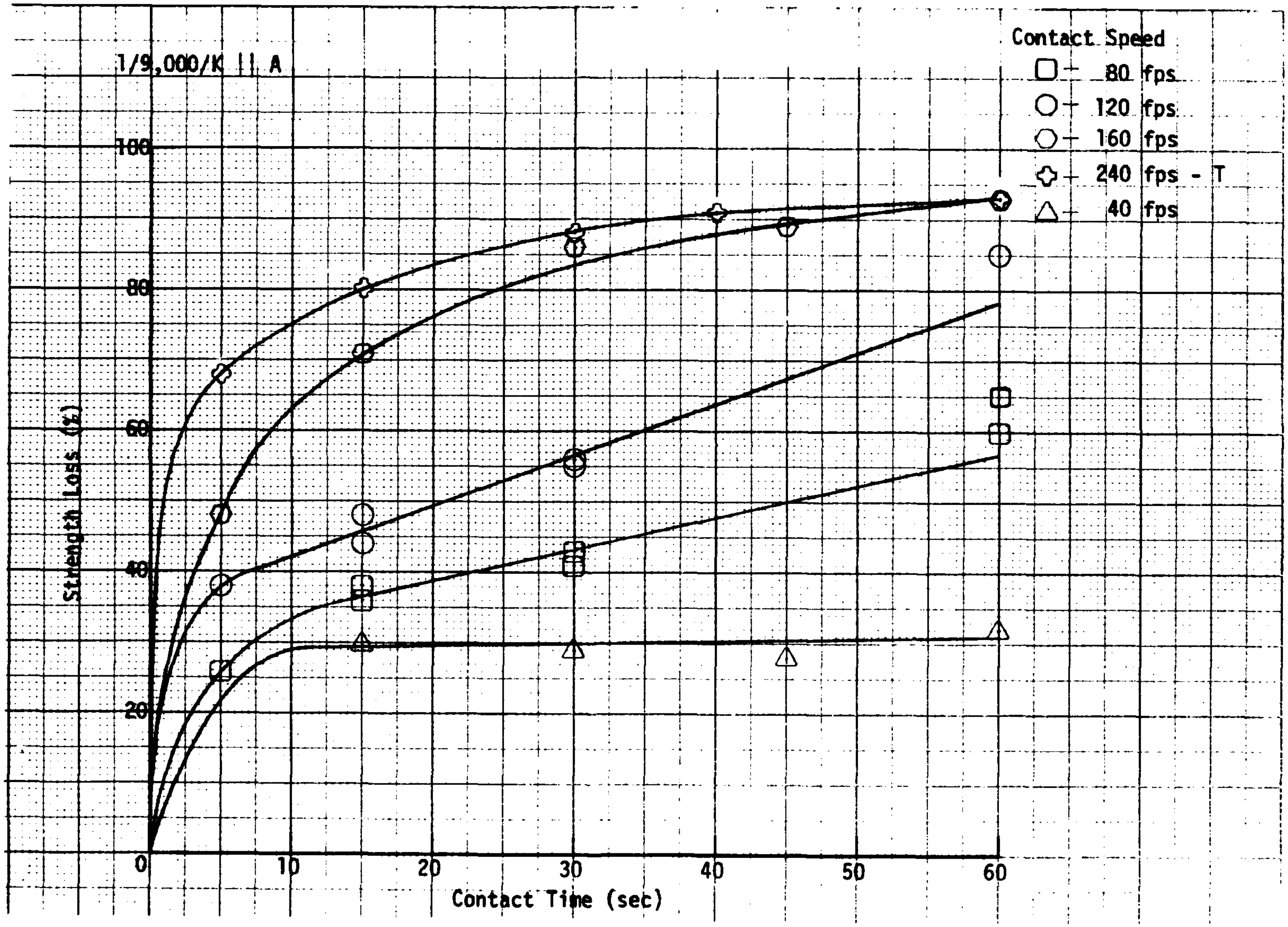


Figure 21. Strength Loss as a Function of Contact Time for a 1 Inch 9,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

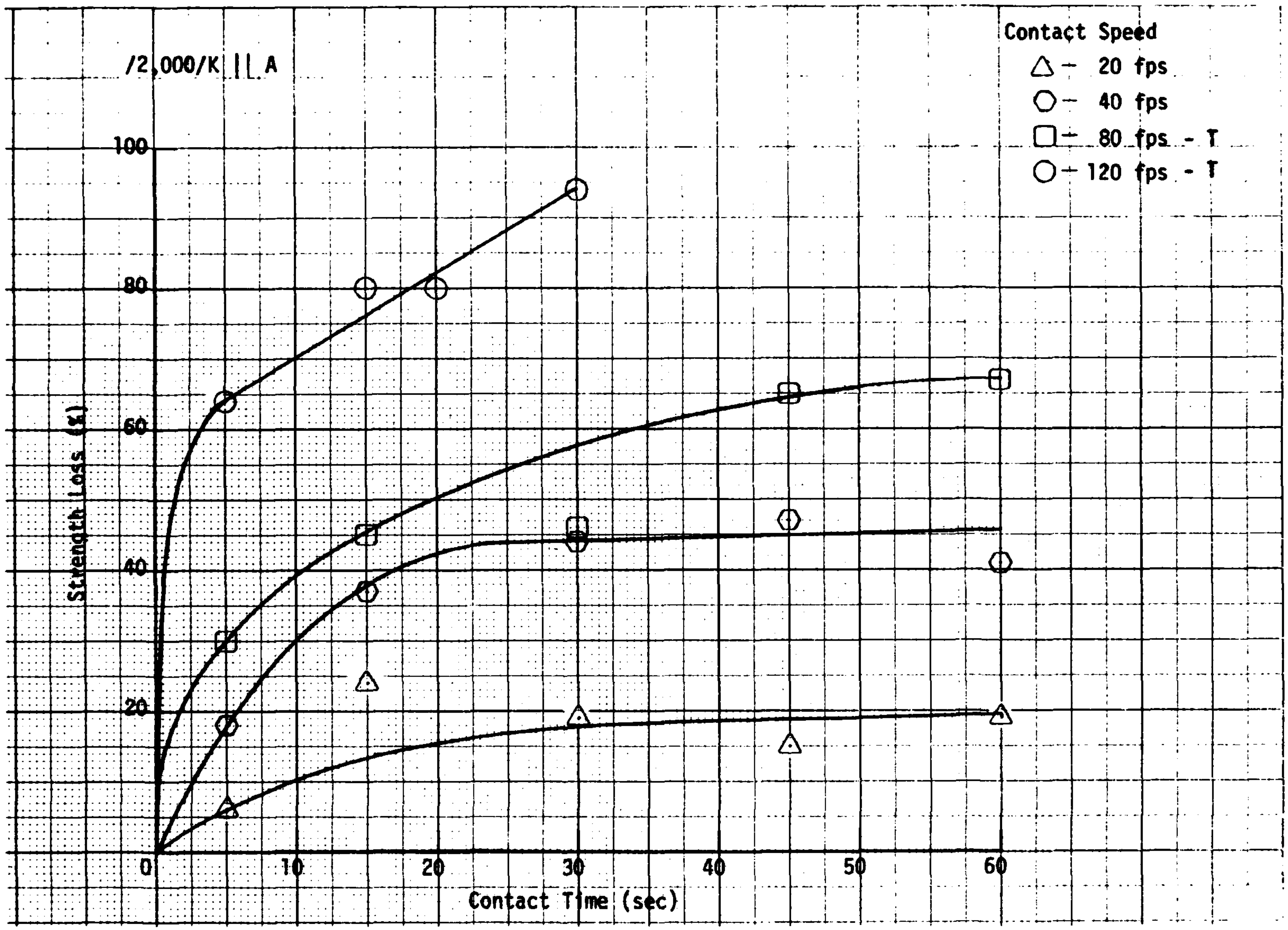


Figure 22. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

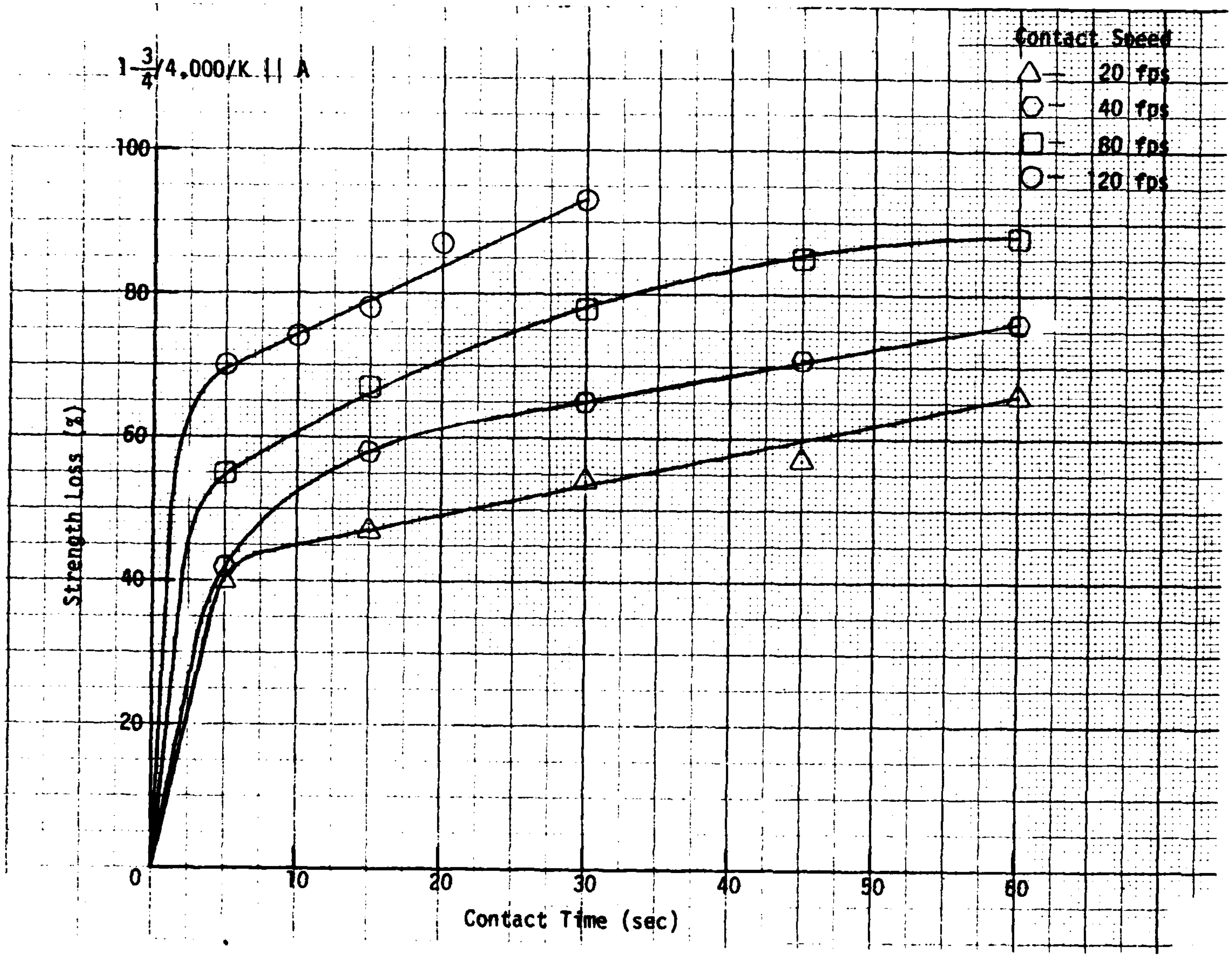


Figure 23. Strength Loss as a Function of Contact Time for a 1-3/4 Inch 4,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

E. 2 Inch 1,000 Lb Kevlar Ribbon

The 1,000 lb Kevlar ribbon was abraded at speeds of 20 and 40 fps using a contact force of 1 lb. Figure 24 presents the results of this testing. Strength losses in this testing were very high. Testing at a speed of 80 fps resulted in immediate failure of the specimen. No scorching was evident in any of the specimens. Tensile breaks were generally poor, occurring as tears. Even though a slow release of the shoe was used, strength losses were very high in the first 5-10 seconds of contact time. After this time a sharp change in the rate of abrasion was seen as evidenced by the curves in Figure 24. This may have been due to the low tension in the specimen, which was actually slack before it was brought into contact with the wheel. This may also be a reason, in part, for the extremely small speed effect found in the testing and indicated in Figure 24.

This ribbon is a plain weave. Close examination of this structure revealed that the yarn crimp was entirely in the warp and therefore, in the initial part of the test, the loading was on the fabric knuckles formed by the passing of the warp yarns over the filling yarns. Inspection of abraded specimens revealed that abrasive damage only occurred on these knuckles. Since the bearing points of these knuckles were small, the effective contact area at the start of the test was only a fraction of the nominal contact area (3"x2"). Also, as these knuckles wore down, the contact area increased rapidly, which effectively lowered the contact pressure and at least in part caused the sharp change in the rate of abrasion.

F. 2 Inch 480 Lb Kevlar Ribbon

The 500 lb Kevlar ribbon was abraded at 20 fps using a contact force of 1 lb. Contact time of only 25 seconds was possible in this testing. No scorching was evident in this testing. Tensile breaks were poor, occurring as a random popping of warp yarns, typical of control breaks also. The results shown in Figure 25 are somewhat unique in that there was a low rate of abrasion initially, which increased with increasing contact time and then decreased after reaching a maximum rate. Close examination of this plain weave construction revealed that the yarn crimp is entirely in the filling, which meant that the initial load bearing occurred on the knuckles of the filling yarns formed by passing over the warp yarns. However, this structure is extremely sleazy and filling yarns were easily skewed even during specimen installation. The filling yarns were skewed and bunched at the start of the test, which exposed warp yarns to be abraded after this initial low abrasion period.

G. 1 Inch 6,000 Lb Nylon Webbing

This material was abraded at speeds of 20, 40, 80 and 120 fps using a contact force of 5 lb. Preliminary tests were also performed using a contact force of 2.5 lb at a speed of 80 fps. Figures 26 and 27 show the results of this testing. Samples abraded at 80 and 120 fps exhibited melting. Tensile breaks on these samples were generally tears. Samples abraded at 20 and 40 fps exhibited no melting and tensile breaks were generally good. The curves associated with testing at the two lower speeds have similar shapes. Both of these curves have slopes which decrease with increasing contact time, becoming nearly linear beyond 15 seconds. The curves associated with test-

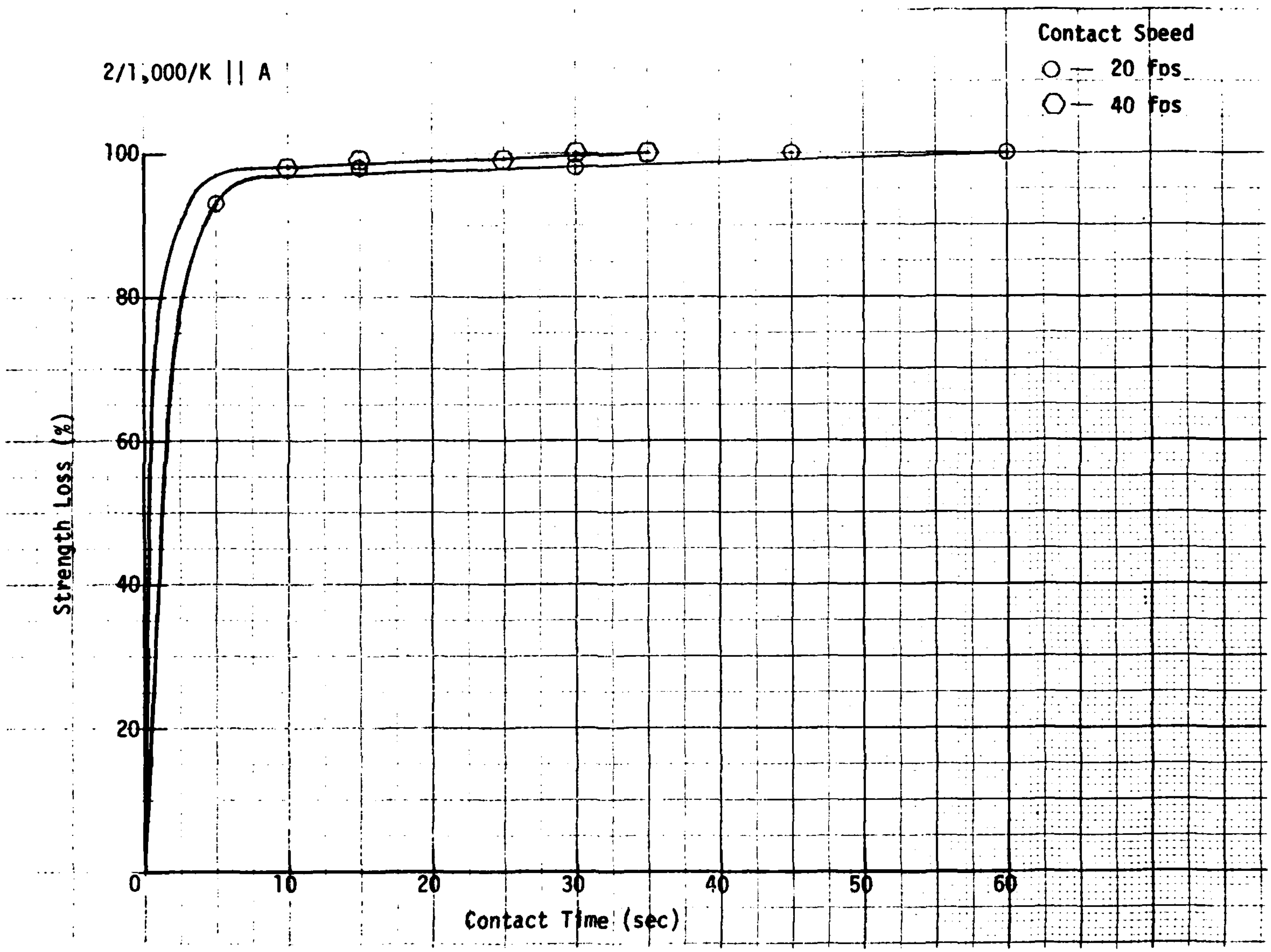


Figure 24. Strength Loss as a Function of Contact Time for a 2 Inch 1,000 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

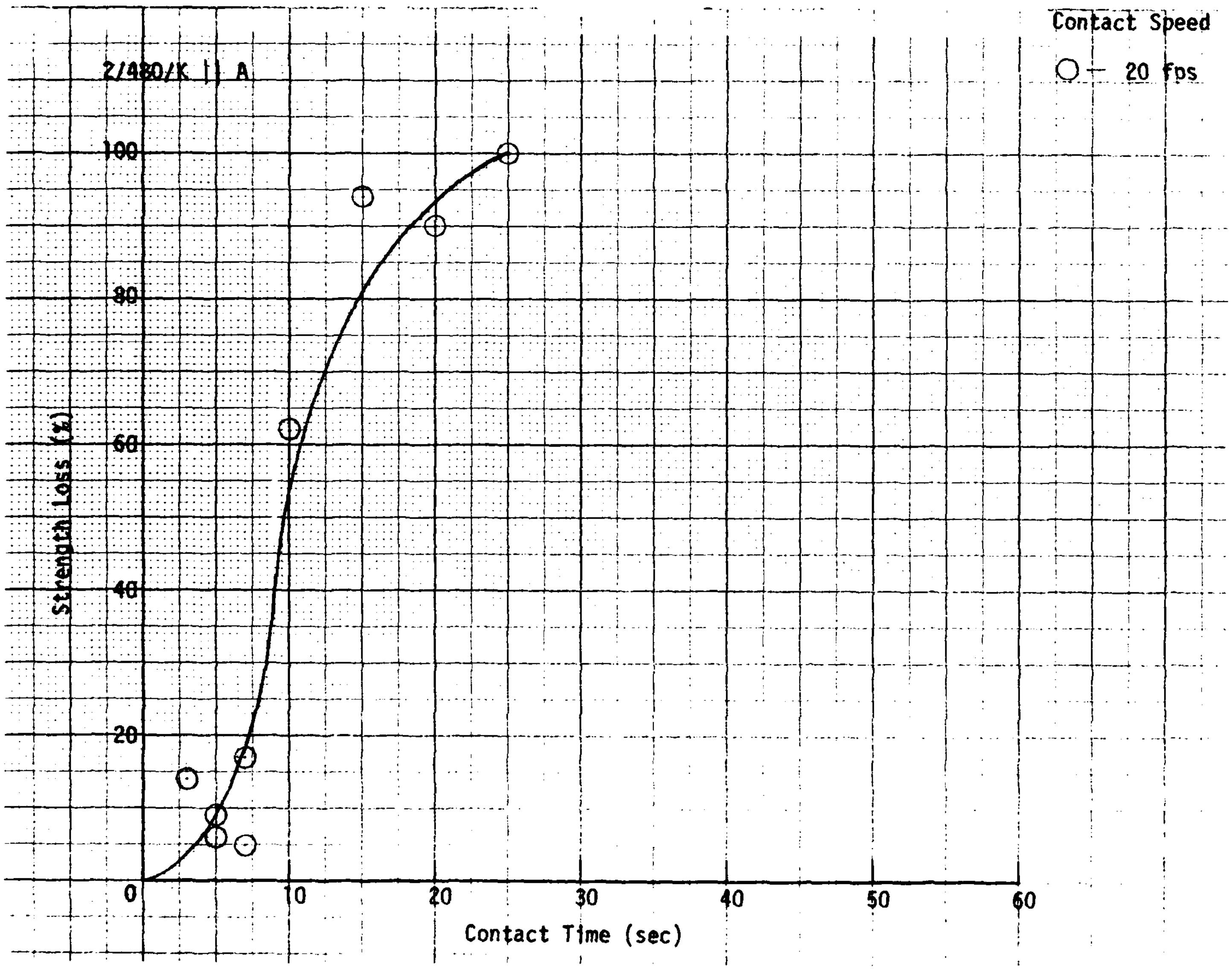


Figure 25. Strength Loss as a Function of Contact Time for a 2 Inch 480 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 1 Lb

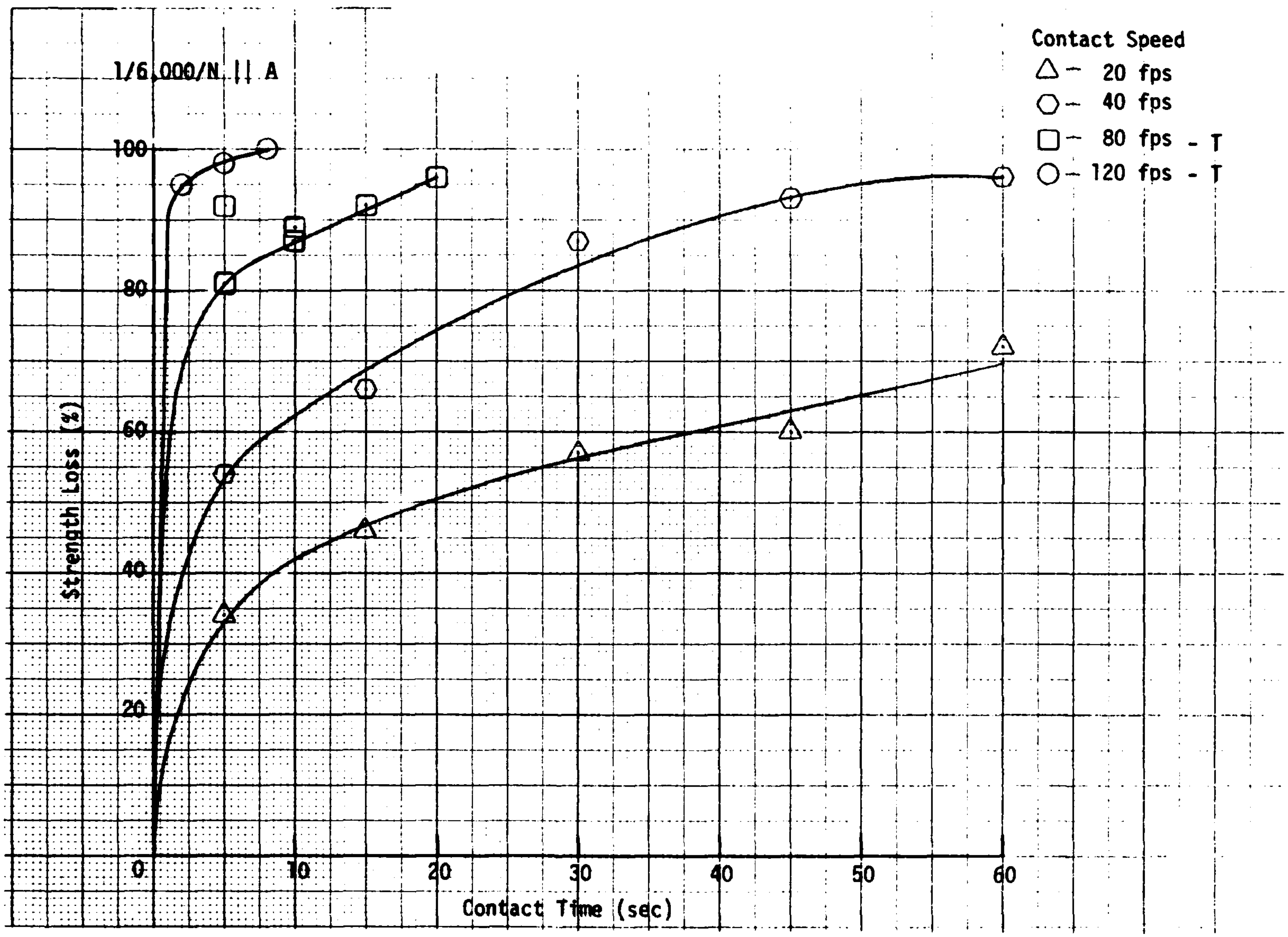


Figure 26. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and Various Contact Speeds

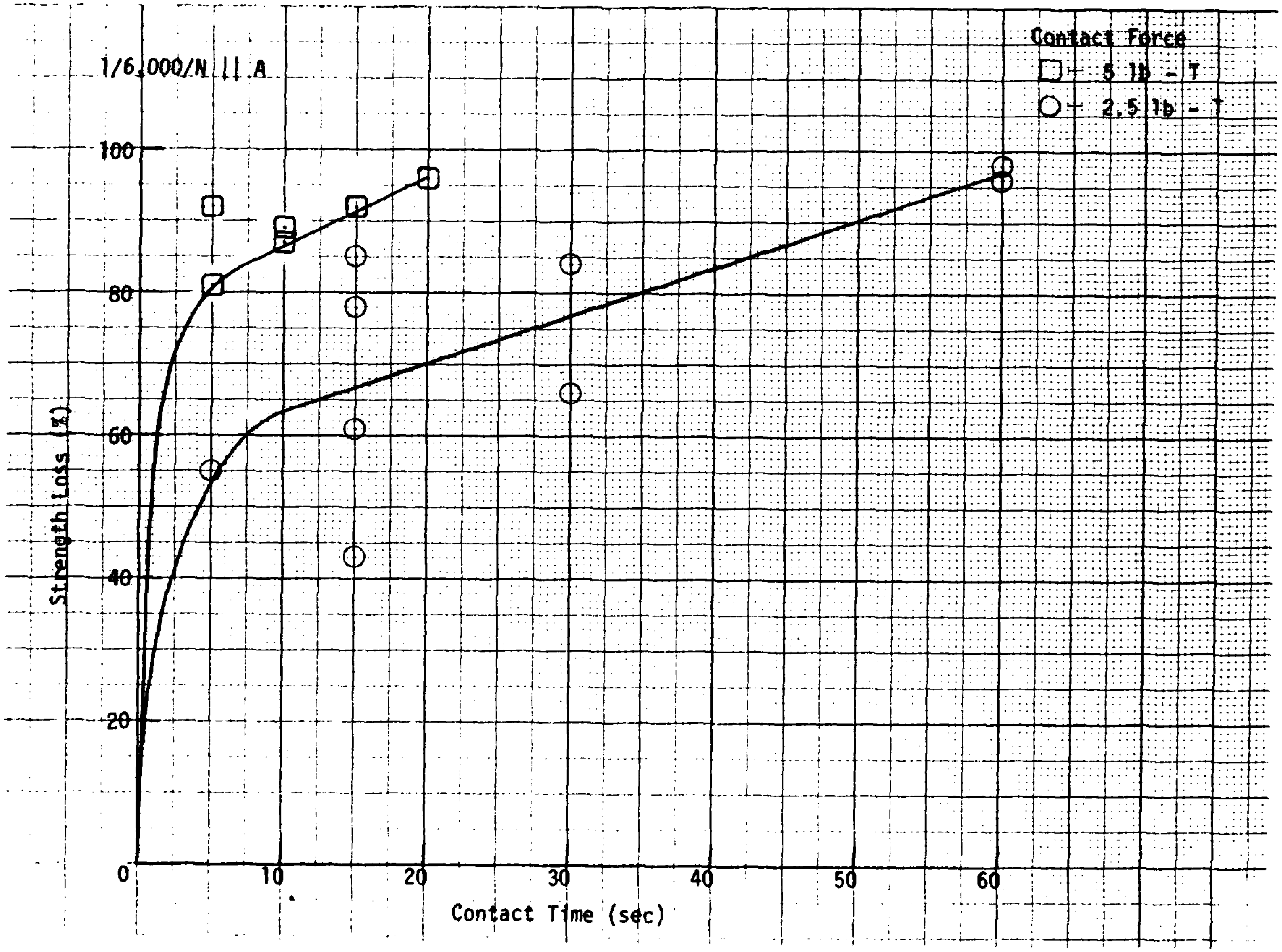


Figure 27. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Abrasive Parallel Configuration at a Speed of 80 fps Using Two Different Contact Forces

ing at the two higher speeds are also similar. The later portion of these curves is linear. This is similar to what was seen in the nylon on nylon testing and is probably due to the melting as it was believed to be in the case of the nylon on nylon testing. The effect of speed still appeared large in this testing. However, it did not appear to be as significant as in the nylon on nylon testing. In this testing, the molten nylon did not stick to the abrasive as it did in the nylon on nylon testing. The molten nylon was pushed out of the abraded area at the trailing edge as the test proceeded. After sufficient buildup of material, it was flung at the side of the machine frame in chunks. This left the abrasive surface free from buildup which may have resulted in slower heat buildup, melting, and migration than in the nylon on nylon testing.

H. 2,000 Lb Nylon Braid

The nylon braid was abraded at speeds of 20 and 40 fps using a contact force of 5 lb in order to get a direct comparison between the Kevlar and nylon braids. Testing attempted at 80 fps resulted in immediate failure of the specimen by melting. Results of the testing at speeds of 20 and 40 fps are given in Figure 28. Tensile breaks in this series were generally good except where extensive damage or melting occurred. Testing at 20 fps yielded no melting. Testing at 40 fps, however, yielded constant melting. Figure 28 illustrates the difference in strength loss as a function of contact time between a melt and a non-melt abrasion situation. As has been seen in previous nylon testing, the melt situation (40 fps curve) results in a linear relationship with a high slope. The residual strength shown in this plot between 95 and 100% strength loss is actually the residual strength of 1 or 2 yarns after most of the yarns had been severed and the balanced structure of the braid was destroyed. The curve associated with testing at 20 fps is similar in shape to what has been seen previously in non-melt test situations. Again the maximum abrasion is seen as a high slope in the initial portion of the curve and the slope decreases with increasing contact time up to a strength loss of 95% at a contact time of 45 seconds. The effect of speed in this testing was again smaller than the effect of speed found in the nylon on nylon testing and the results were much more consistent.

I. 2 Inch 1,000 Lb Nylon Ribbon

The 1,000 lb nylon ribbon was abraded at speeds of 20, 40, 80 and 120 fps using a contact force of 1 lb. The results are given in Figure 29. No melting was evident in any of the test specimens. Tensile breaks in this series were good except for specimens tested at 120 fps which tended to tear. Variability of results was generally low. The curves in Figure 29 are typical in that the rate of abrasion was a maximum initially, decreased with increasing contact time and approached zero in some instances. The lack of a pronounced knee in these curves was possibly due to the twill weave construction (2 over, 2 under) which eliminated pronounced knuckles and resulted in an effective contact area which was a high percentage of the nominal contact area (3"x2"). Therefore, the contact area changed slowly as the test proceeded as evidenced by the slow change in rate of abrasion as the test proceeded even though the warp bore all of the contact force. There also seemed to be a greater speed effect present in this testing than in the testing of the lightweight Kevlar materials.

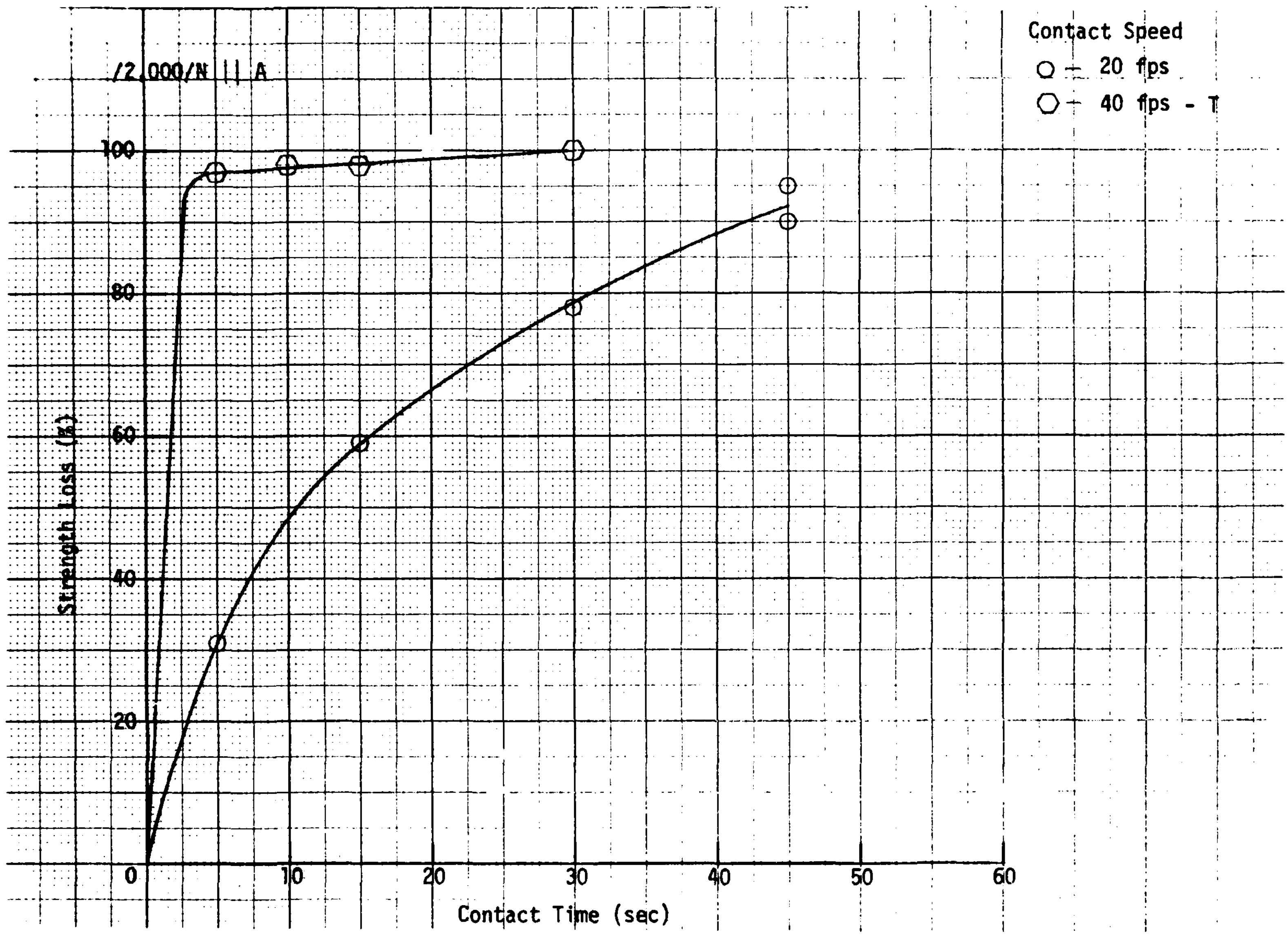


Figure 28. Strength Loss as a Function of Contact Time for a 2,000 Lb Nylon Braid Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and Two Different Contact Speeds

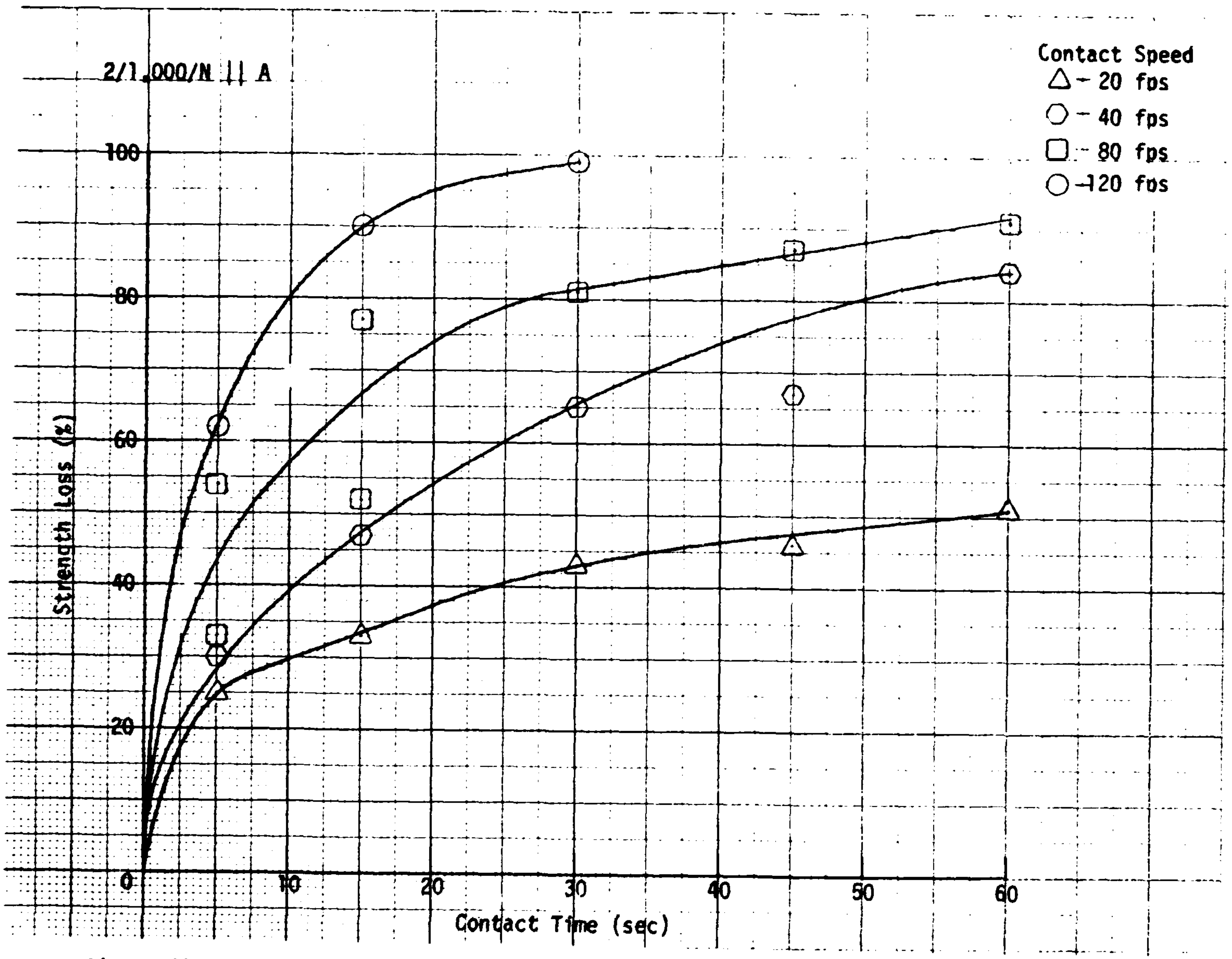


Figure 29. Strength Loss as a Function of Contact Time for a 2 Inch 1,000 Lb Nylon Ribbon Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

J. 2 Inch 460 Lb Nylon Ribbon

The 460 lb nylon ribbon was abraded at speeds of 20, 40 and 80 fps using a contact force of 1 lb. The results are given in Figure 30. No melting was evident in any of the specimens. Variability was low. Tensile breaks occurred typically as tears. Strength losses in this testing were high and speed effects were small. The curves in Figure 30 are similar to those for the lightweight Kevlar materials in that high strength losses were seen initially followed by a marked change in the rate of abrasion. This construction is also a twill weave (2 under, 2 over) similar to the 1,000 lb nylon ribbon. However, it has far fewer warp ends and a higher pick frequency which resulted in more pronounced fabric knuckles and fewer of them. This reduced the effective contact area even though the yarn crimp is partially shared by the filling yarns due in part to the sleaziness of the material. This material acted more like the plain weave Kevlar ribbons than its nylon counterpart.

K. Kevlar/Nylon Comparison

1. Webbings

The three heavy webbings were all abraded using a contact force of 5 lb. Contact speeds common to testing of all three webbings were 40, 80 and 120 fps. For comparison purposes, test results for each of the three webbings were plotted together for each of the three test speeds in Figures 31 through 33. Figure 31 shows the results of testing at 40 fps for all three webbings. No melting or scorching was evident in any of the specimens. These results show significantly better abrasion resistance of Kevlar than nylon. Even the 6,000 lb Kevlar webbing, whose construction and surface characteristics were not ideal for abrasion resistance due to the pronounced knuckles, performed significantly better than the 6,000 lb nylon webbing. The 9,000 lb Kevlar webbing more closely resembled the 6,000 lb nylon webbing in weight, thickness, construction and surface characteristics. Its abrasion resistance was far superior to that of the nylon webbing and also superior to the 6,000 lb Kevlar webbing. Figures 32 and 33 show similar relationships for testing where nylon exhibited melting at speeds of 80 and 120 fps. This data shows the superior abrasion resistance of Kevlar webbings over nylon webbings when they are rubbed with a common abrasive surface under similar conditions even when thermal effects were minimized.

2. Braids

The results of braid testing were also plotted in this manner since they too were both abraded using a contact force of 5 lb. Figures 34 and 35 compare the results of tests conducted with the two braids at speeds of 20 and 40 fps respectively. Figure 34 shows data for a non-melt, no-scorch situation. Even though the nylon braid did not sustain high strength losses in extremely short times, it did sustain a 90% loss in 45 seconds of rubbing. The Kevlar braid exhibited only minor damage and strength loss up to 60 seconds contact time. In the melt situation (Figure 35), the nylon braid exhibited a 95% strength loss in 3 seconds contact time. The Kevlar braid abraded at 40 fps exhibited approximately twice the amount of abrasive damage and strength loss that it exhibited at 20 fps. In addition to this, the Kevlar braid is only half the size of the nylon braid and therefore had a

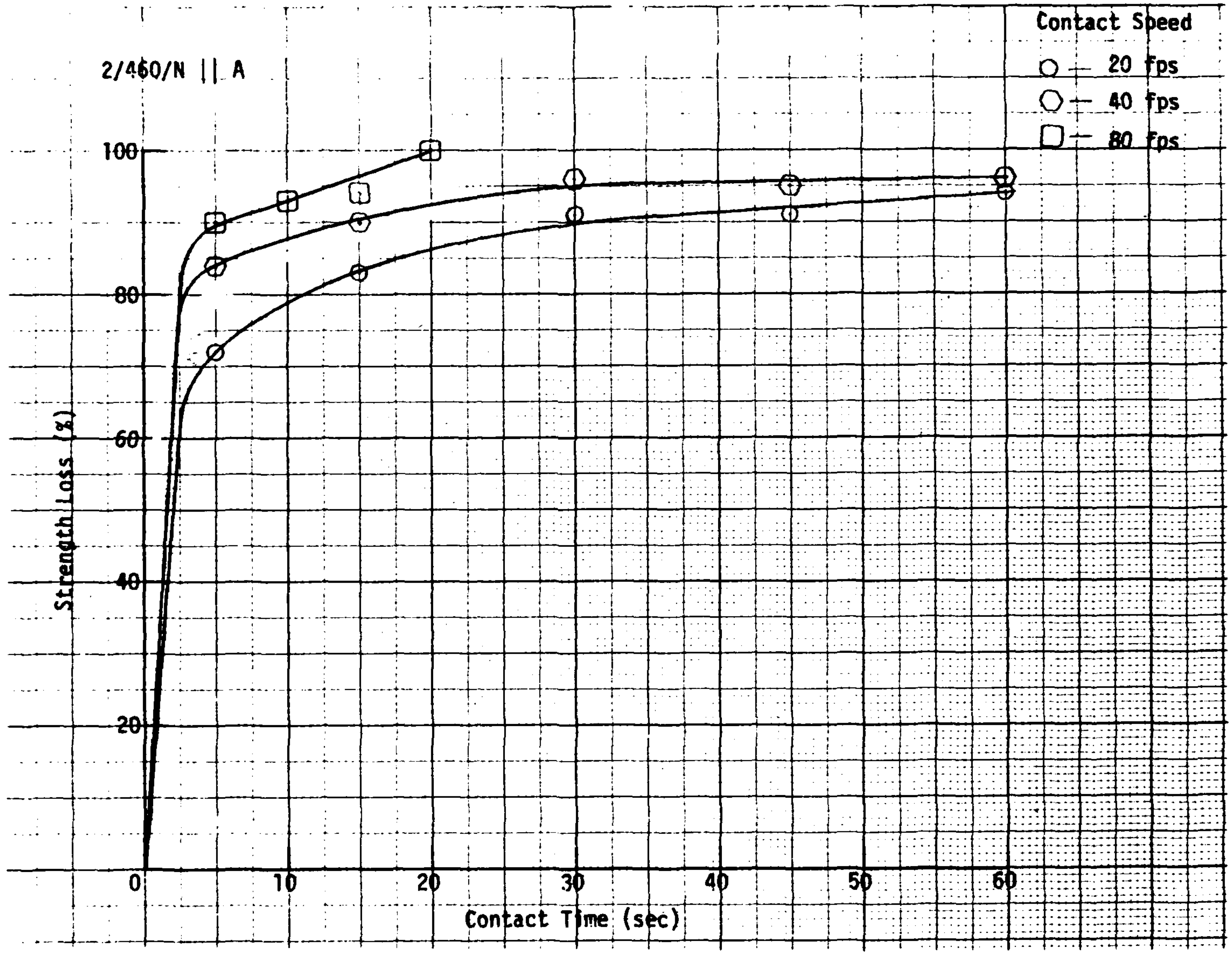


Figure 30. Strength Loss as a Function of Contact Time for a 2 Inch 460 Lb Nylon Ribbon Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

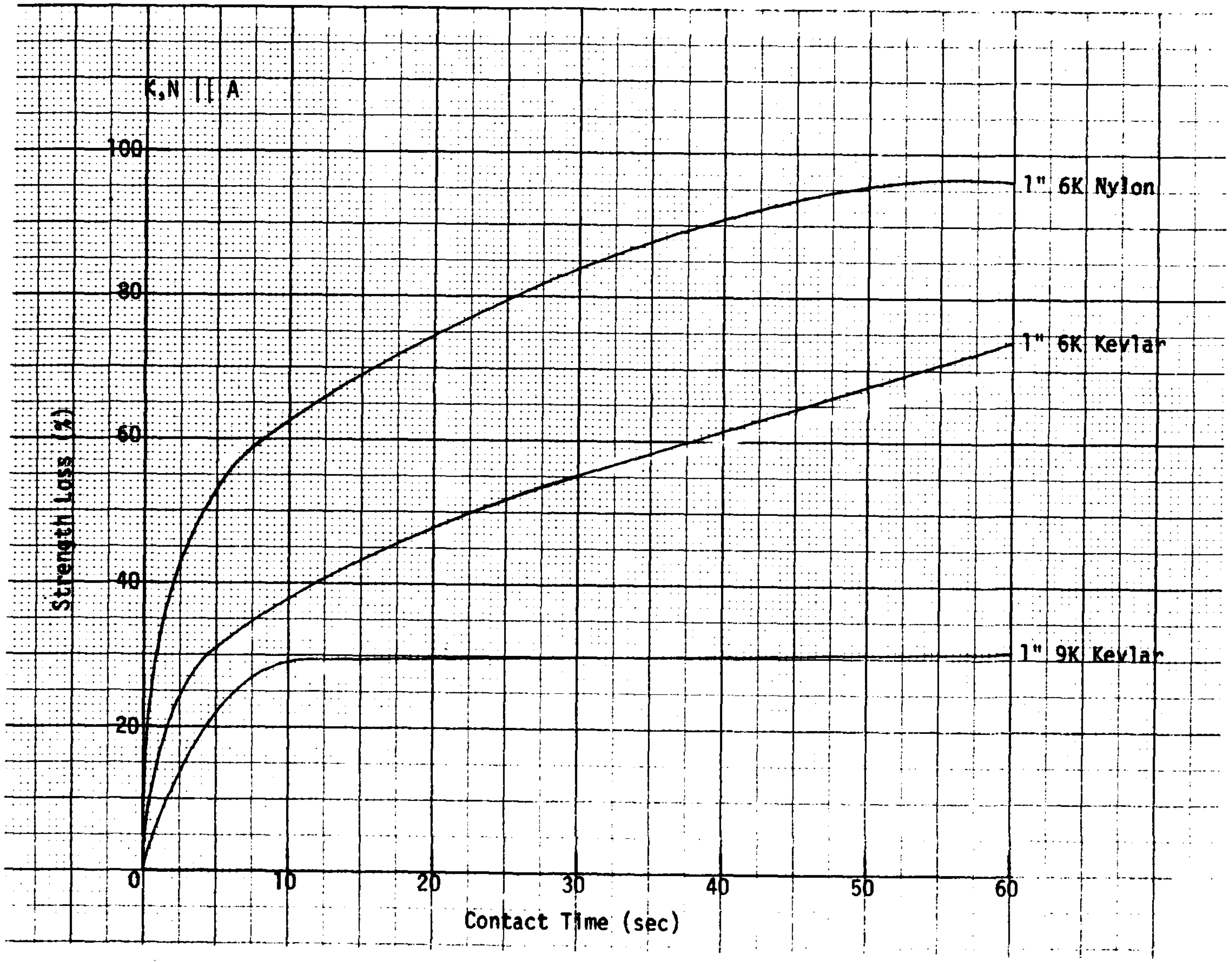


Figure 31. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 40 fps Using a Contact Force of 5 Lb

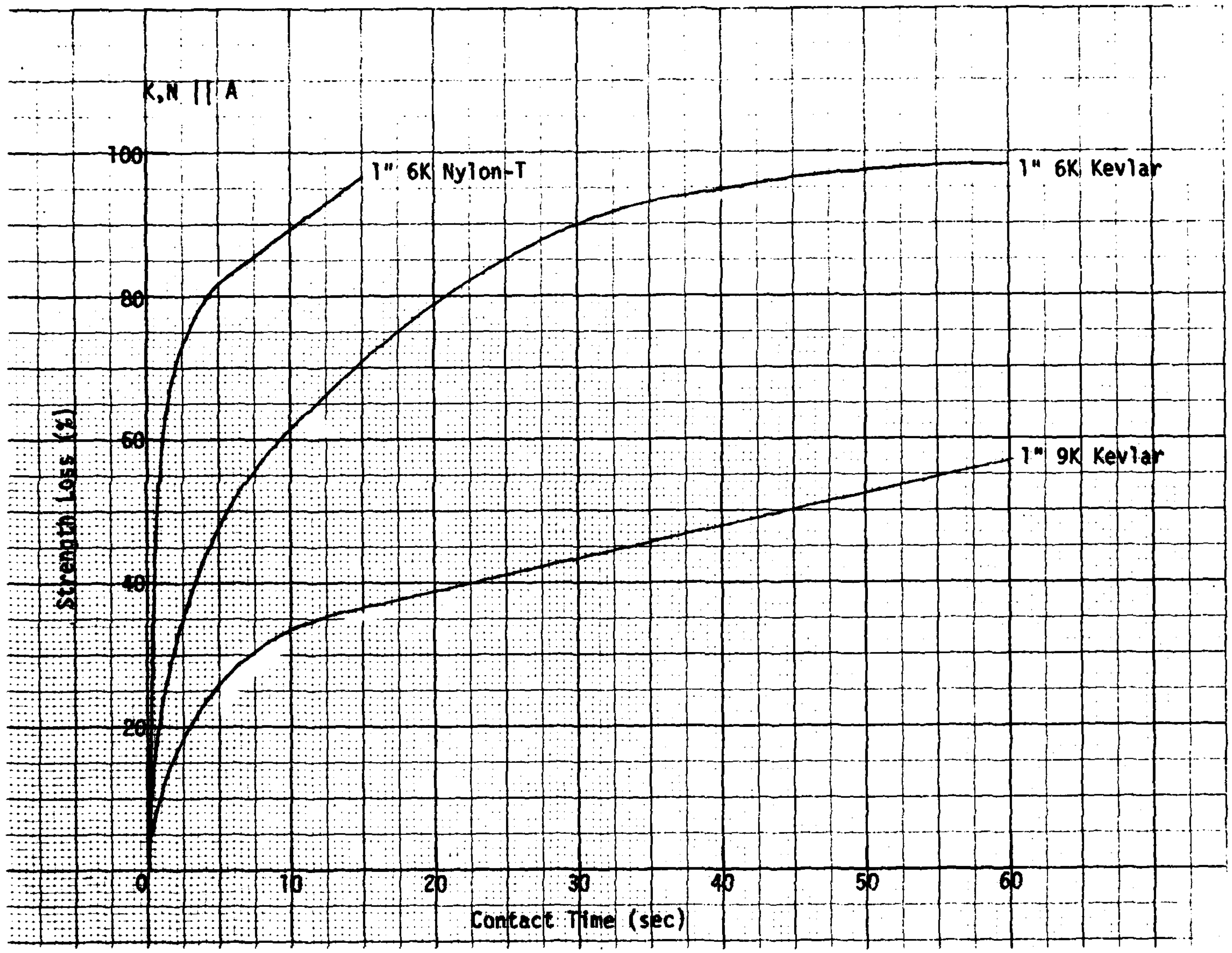


Figure 32. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 80 fps Using a Contact Force of 5 Lb

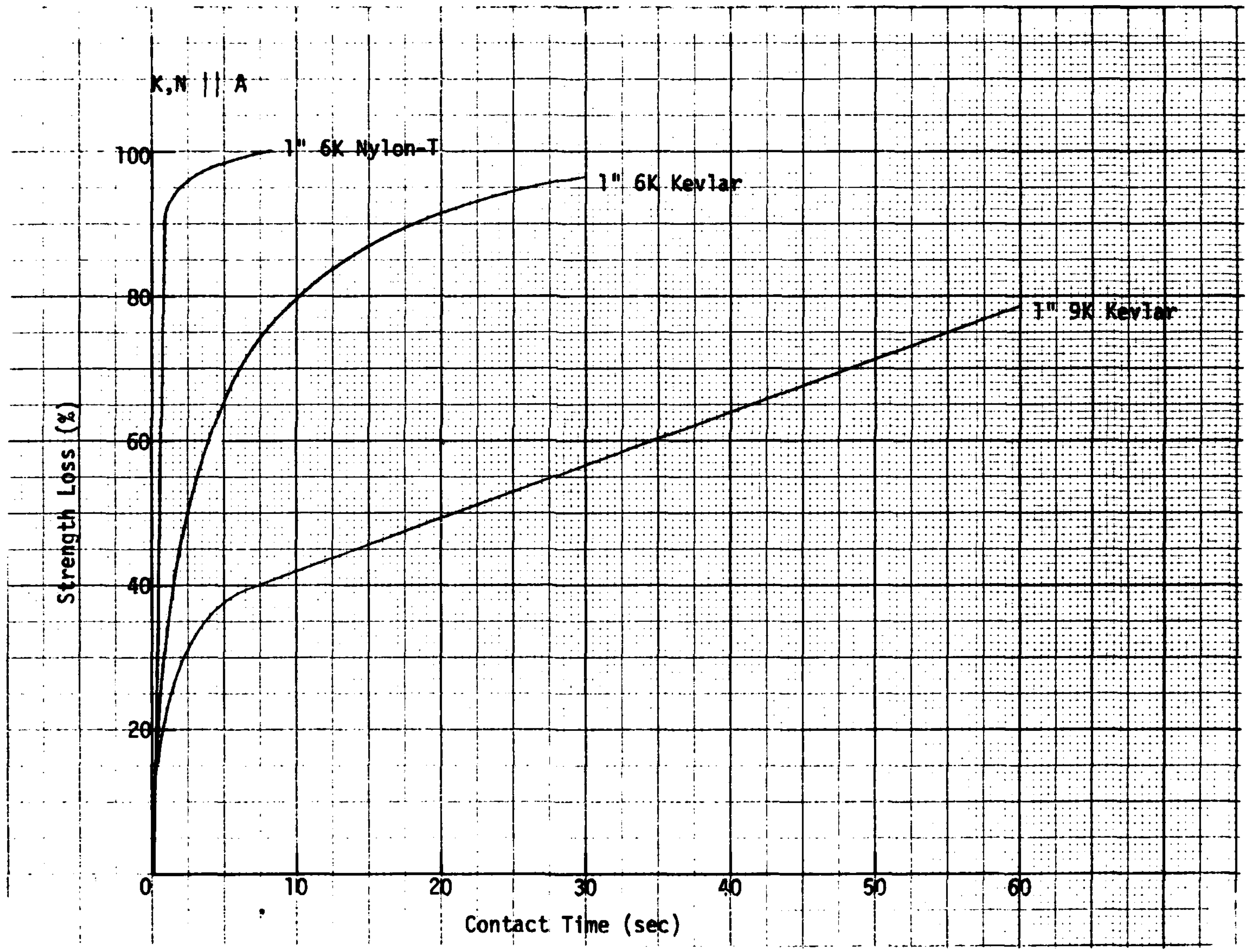


Figure 33. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 120 fps Using a Contact Force of 5 Lb

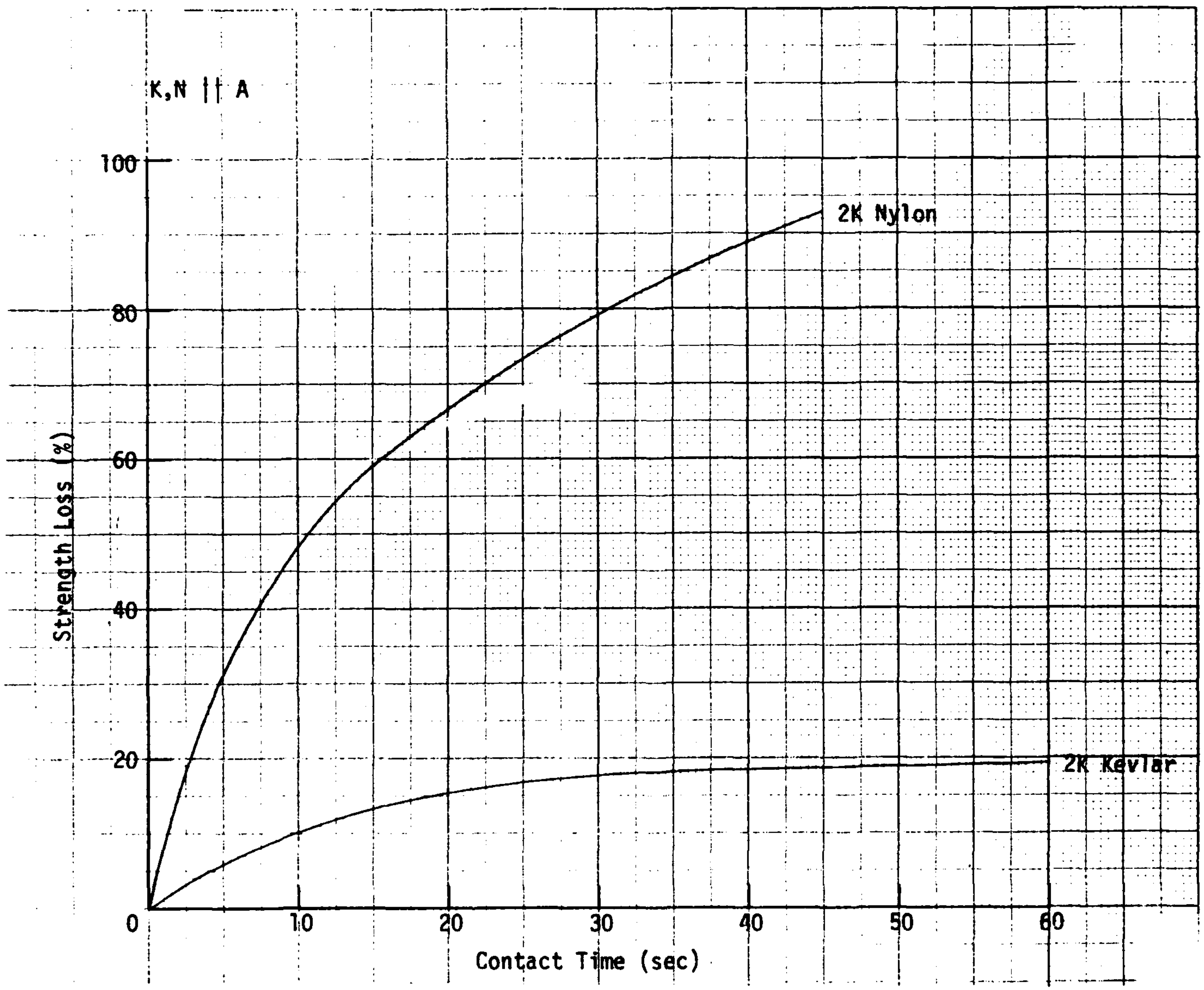


Figure 34. Strength Loss as a Function of Contact Time for Two Braids Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 20 fps Using a Contact Force of 5 Lb

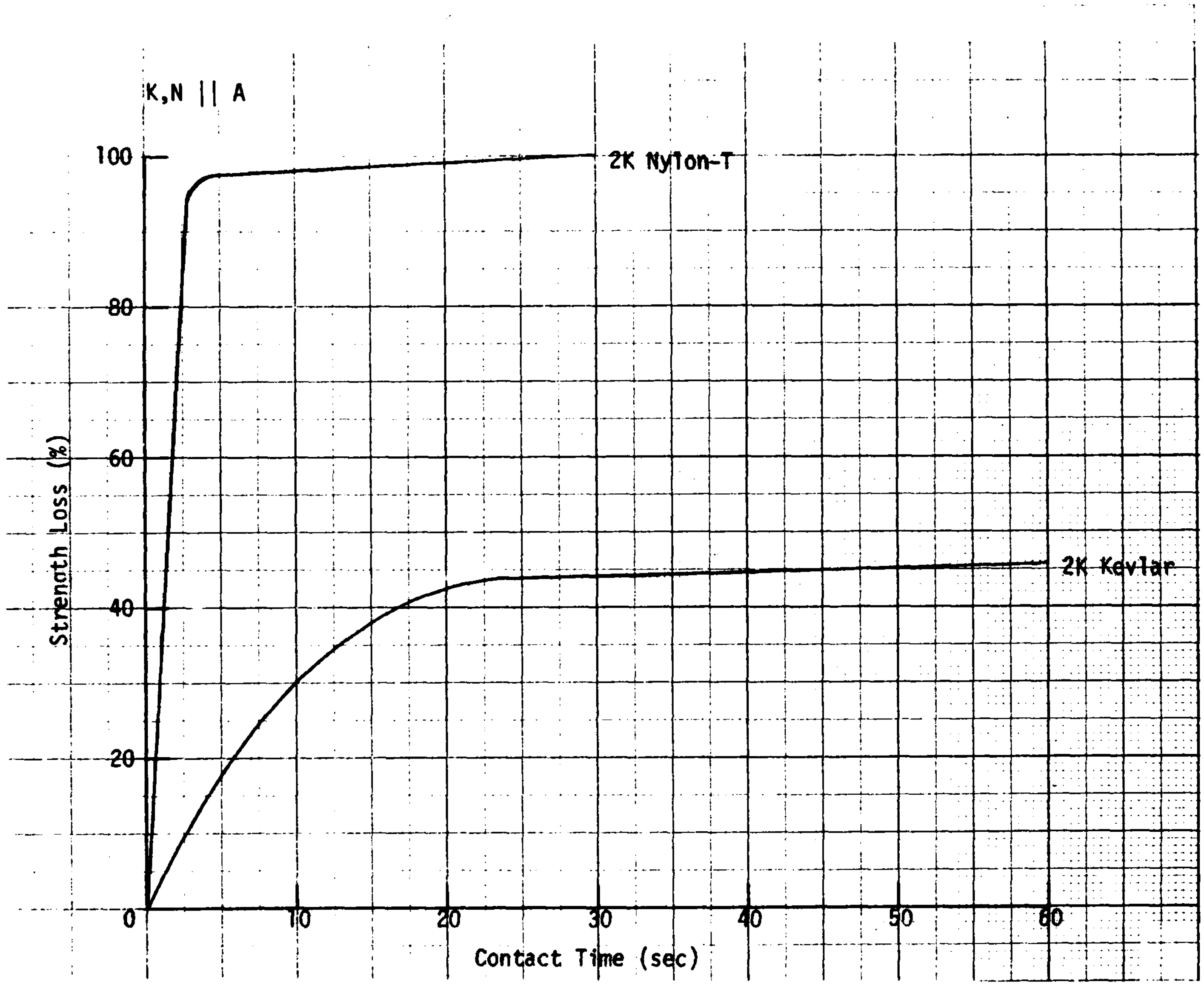


Figure 35. Strength Loss as a Function of Contact Time for Two Braids Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 40 fps Using a Contact Force of 5 Lb

contact pressure exerted on it of approximately twice the contact pressure exerted on the nylon braid. This data again shows the superior abrasion resistance of Kevlar braid over nylon braid when rubbed by a common abrasive surface under similar conditions.

3. Ribbons

The ribbons (and 4,000 lb Kevlar light webbing) were abraded using a contact force of 1 lb. With the exception of the 1-3/4 4,000 lb Kevlar webbing, all were 2 inches wide and thus had nominally equal contact areas. Figure 36 shows the results of testing at 20 fps for all five materials. The 2 inch 1,000 lb nylon ribbon performed the best overall in this testing. Initially the 480 lb Kevlar ribbon showed the least strength loss because of the protection of the warp yarns by the crimped filling yarns. After these yarns became skewed, the strength losses sustained by this ribbon were high in a very short time. The other two Kevlar materials faired poorly in this testing. Both are plain weaves with warp yarns exposed on the fabric surface as knuckles. These knuckles therefore represent the bearing surface for contact with the abrasive surface. The effective area of contact is less than half of the nominal contact area at the start of the test. As the knuckles wear, the area increases and the pressure drops. However, the area of contact can never exceed 50% of the nominal contact area unless the filling supports the load also. However, the tension in the specimen is too low to pull out the warp crimp and introduce enough crimp in the filling to bring the yarns out of the fabric surface. Close inspection of the abraded specimens revealed this to be true. Even under the harshest of conditions, abrasive damage was limited to the warp yarns at the apex of the knuckles.

The abrasion resistance of both nylon ribbons was quite good when compared with that of the Kevlar materials in this testing. A discussion of the constructions of these ribbons was presented in Section VII, I and J. The construction of the 1,000 lb nylon ribbon results in long flat floats (knuckles) on the fabric surface with the filling yarns buried in the structure. This yielded an effective contact area which seemed to be greater than 50% of the nominal contact area. Also, because of the flatness of the floats, the effective contact area remained fairly constant during the test. The abrasion was therefore directed more along the longitudinal axis of the yarn than through its thickness as in the case of the Kevlar ribbons. This resulted in a more tensile type failure of nylon filaments as the abrasive particles snagged them, indicated by long lengths of disoriented and broken filaments on the abraded surface. This was opposed to the shearing type of fiber failure in Kevlar at the pronounced knuckles, evidenced by the flat abraded area on the knuckle and broken fiber protruding vertically at the leading and trailing edges of the knuckles. Kevlar, being a highly oriented fiber in the longitudinal direction, is weak in the transverse direction.

The 460 lb nylon ribbon also performed well in this testing as discussed in Section VII, J, this material has fewer ends and a higher pick frequency resulting in shorter more rounded floats than the 1,000 lb nylon ribbon. In this construction however, a small amount of tension caused a straightening of warp yarns and crimping of filling yarns, thereby forcing the filling yarns to the surface of the fabric. This was evidenced by the presence of broken filaments in the filling yarn as well as the warp yarns. The result was an effective contact area which appeared to be greater than 50% of the nominal contact area and a sharing of abrasive damage between the load bearing warp yarns and the filling yarns.

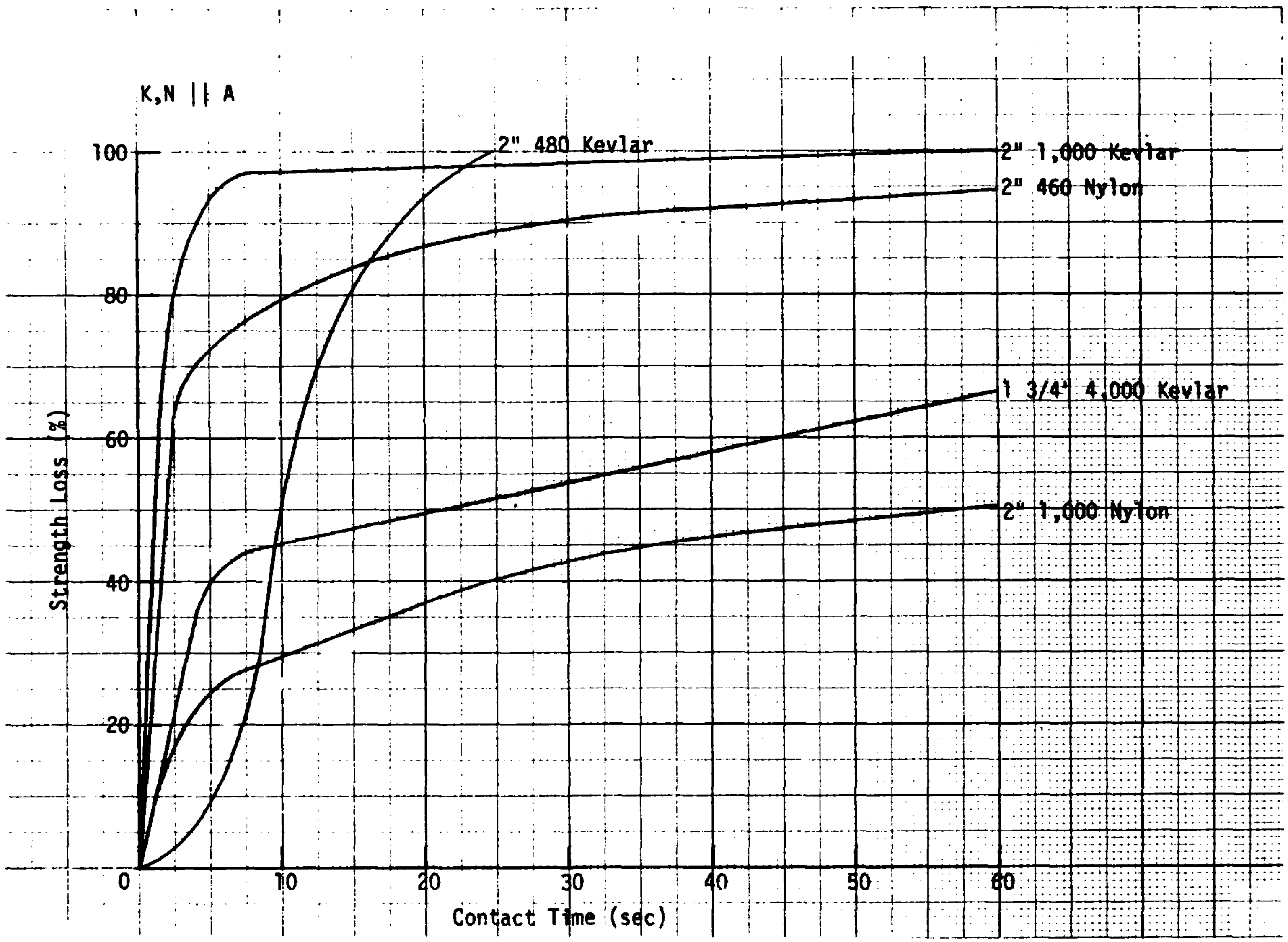


Figure 36. Strength Loss as a Function of Contact Time for Five Ribbons Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 20 fps Using a Contact Force of 1 Lb

Figure 37 shows the results of testing performed at 40 fps. The 480 lb Kevlar ribbon could not withstand testing at this speed. In general, the constructional parameters discussed previously apply in this testing also. The performance of the 1,000 lb Kevlar ribbon and the 460 lb nylon ribbon in this testing was very similar to what was seen in testing of 20 fps. The 1-3/4 inch 4,000 lb Kevlar webbing sustained somewhat higher strength losses at this speed as did the 2 inch 1,000 lb nylon ribbon. The consistency of the effective contact area of the 1,000 lb nylon ribbon is evidenced by the relatively linear curve in Figure 37. The increased contact area and therefore decreased rate of abrasion for the 4,000 lb Kevlar webbing at the longer contact times resulted in strength losses which were lower than those for the 1,000 lb nylon ribbon in this region.

4. Summary

In general, direct comparisons of abrasion resistance between Kevlar and nylon cannot be made from the results of this testing due to constructional effects which were discussed previously. However, comparisons between particular materials can be made, inclusive of constructional effects. The Kevlar webbings and braid demonstrated far superior abrasion resistance than nylon even though test conditions and/or constructional effects often favored the nylon materials. This was true in the case of both melt and non-melt situations. It should be noted, however, that the non-melt situations were not necessarily devoid of thermal effects since some specimen heating must have occurred during rubbing and nylon typically loses 50% of its strength at 350°F while Kevlar loses only about 10% of its strength at this temperature[4]. In general, the nylon ribbons demonstrated better abrasion resistance than the Kevlar ribbons. Here, however, test conditions and especially constructional effects appeared to be the major reason for this difference in performance. Comparisons made between materials on the basis of strength, as for example between the 1,000 lb Kevlar and nylon ribbons, is out of line not only because of constructional effects discussed previously, but also due in part to an almost 3-fold difference in fabric weight and thickness. A comparison on the basis of weight and thickness for these materials would have to be between the 1,000 lb nylon and the 4,000 lb Kevlar materials. Figures 36 and 37 reveal the similarities in performance between these two materials even though constructional effects and test conditions (2"x3" nominal contact area for nylon as opposed to 1-3/4"x3" for the Kevlar) tended to favor the nylon ribbon. Even between the 1,000 lb Kevlar and 460 lb nylon ribbons where, aside from constructional surface effects, there is a 2-fold difference in weight and thickness in favor of the nylon ribbon, similarities in performance were obvious. In summation, even though constructional differences make rating of these two materials for relative abrasion resistance a difficult if not impossible task, there was no indication in this that Kevlar's abrasion resistance was poor, or even worse than that for highly abrasion resistant nylon. Most indications were that the abrasion resistance of Kevlar in a situation of high speed rubbing on an abrasive surface was superior to that of nylon.

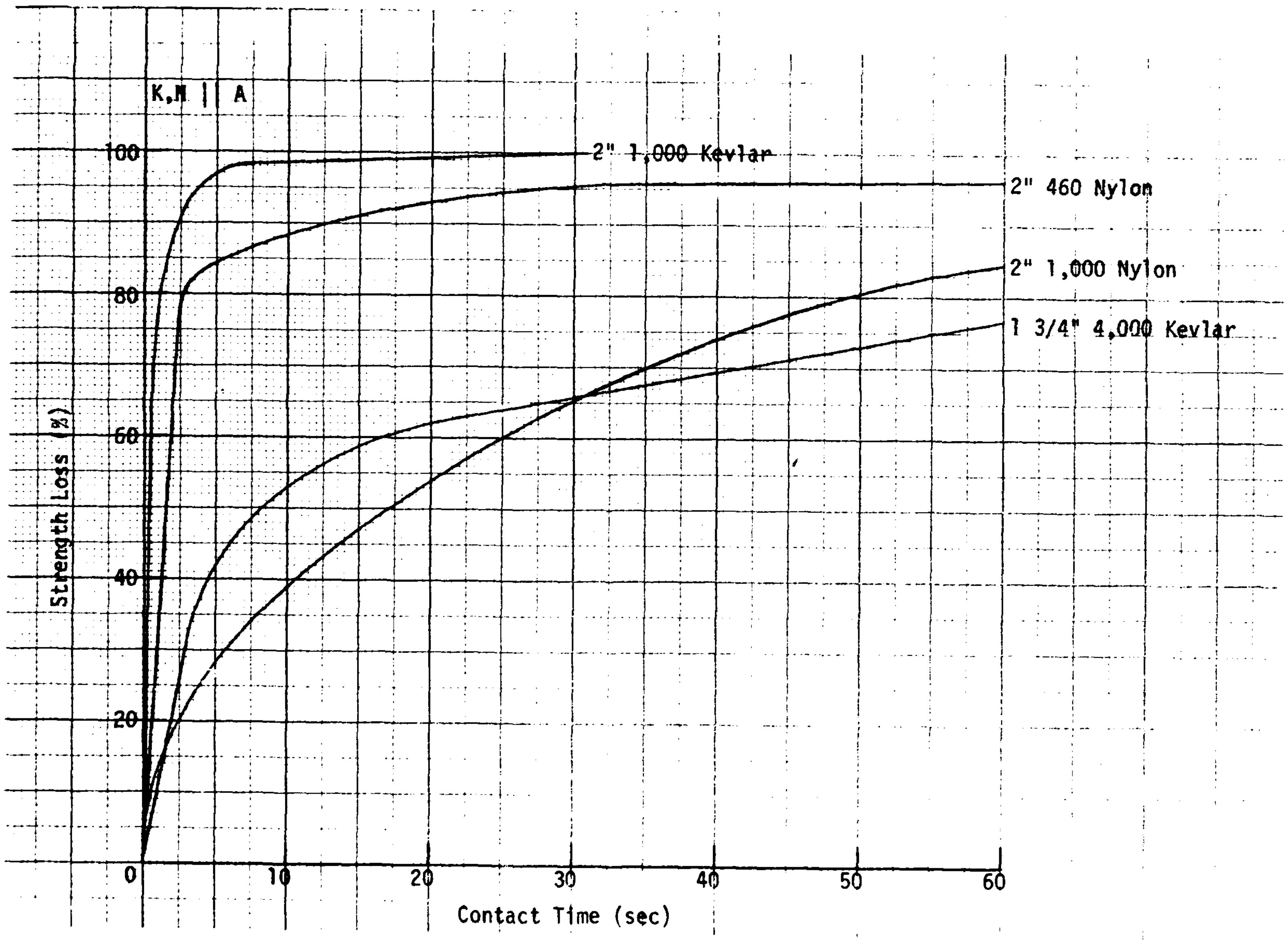


Figure 37. Strength Loss as a Function of Contact Time for Four Ribbons Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at 40 fps Using a Contact Force of 1 Lb

SECTION VIII

KEVLAR (NYLON) ON ABRASIVE SURFACE PERPENDICULAR ABRASION

Problems were encountered with testing in this configuration that were not present in the Kevlar on Kevlar testing. Long contact times with the heavier webbings and braids often resulted in the leading edge being folded under by the frictional forces. In the case of the braid this occurred as a rolling of the sample. This resulted in uneven abrasion of the edges, poor tensile breaks and high variability. Since this problem was not controllable in the test, it was necessary to slightly curl the leading edge of the webbing to avoid the problem. With the braid, the only possible solution was to carefully install the sample so that there was no twist in the free length which might help the rolling action.

The loading configuration also caused some unavoidable problems. The deflection of the sample was caused by its bearing against the flat 2 inch wide abrasive strip. The loading was therefore slightly higher at the edges of the abrasive strip. This caused uneven abrasion along the length of the specimen with the maximum occurring at the limits of the abraded area. The pivot for the lever arm was positioned to maximize tension in the abraded specimen and minimize deflection, therefore, minimizing the unevenness of the abrasion. However, the lightweight ribbons presented further problems. The tension needed in the sample in this configuration represented a significant portion of the full strength of the material. Testing in this configuration resulted in tearing of the specimens as yarns were weakened. This resulted in holes in the abraded area and distortion of the specimen due to the imbalance initiated by broken yarns and magnified by the high tension in the specimen. It was necessary, in ribbon testing, to lower the pivot for the lever arm, thereby lowering specimen tension and increasing specimen deflection. In this configuration, we were able to run longer contact times with the ribbons. However, abrasion at the edge of the abrasive strip was increased causing further unevenness in the abrasion. Although this is still not an optimum configuration, it was felt that it was a better situation than what had been used previously. Individual test results are presented in Table 10.

A. 1 Inch 6,000 Lb Kevlar Webbing

Figure 38 presents the results of testing the 6,000 lb Kevlar webbing abraded at speeds of 20, 40, 80 and 120 fps using a contact force of 2.5 lb. No scorching was evident in any of the specimens. Tensile breaks in this series were generally poor occurring as tears. There were some simultaneous failures which occurred at the edge of the abraded area. Tears were generally initiated at the leading edge which seemed to sustain more abrasive damage than the trailing edge.

The curves in Figure 38 have similar shapes and exhibit good parallelism. As usual the slope of the curves is highest initially, decreasing with increasing contact time. This would again indicate a reduction in the abrasive power of the abrasive and/or a reduction in contact pressure as the fabric knuckles wore away and the fabric became filled with broken fibers. This type of change in surface characteristics of both the webbing and the abrasive paper could also have caused a reduction in the coefficient of friction between the two. Variability of test results was generally low considering the problems associated with this test configuration.

TABLE 10

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PERPENDICULAR CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	2.5	20	6,040		31		42			66			59		62
	2.5	40	6,040		41		58			78			72		77
	2.5	80	6,160		82 55[1]		70 80[1]			89			91 86		
	2.5	120	6,160		97 84 69	77 77	89 87	93	91[2]						
1 inch 9,000 lb Kevlar Webbing	2.5	20	9,900		9		23			36			47		41
	2.5	40	9,900		20		36			47			49		58
	2.5	80	9,900		27		44			58 58			60 67[3]		73
	2.5	120	9,900		29		52			69			80		86
2,000 lb Kevlar Braid	1	20	2,180		35		56			56			77		86
	1	40	2,180		39	71 67	66 81	54	75	86 93					
	1	80	2,180		67	80 90[4]									

TABLE 10 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PERPENDICULAR CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1-3/4 inch 4,000 lb Kevlar Webbing	1	20	4,170		57		62			75 75 75			77 78 80		83
	1	40	4,170		52	64	57	77		80			86		
	1	80	4,170		71	77	82	89		91	99[5]				
	1	120	4,170		73	83	89								
2 inch 1,000 lb Kevlar Ribbon	1	20	880		85		90			94			94 100		
	1	40	880		86	90	96	100[6]							
	1	80	880	90	97										
2 inch 480 lb Kevlar Ribbon	1	20	450	44	70	93[7]									
1 inch 6,000 lb Nylon Webbing	2.5	20	6,740		35		47			63			67		69
	2.5	40	6,740		45		64			72			85		85
	2.5	80	6,740		70	81	85 89 87 86	94	96						
	2.5	120	6,740		86	97 89[8]									

TABLE 10 (cont.)

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PERPENDICULAR CONFIGURATION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
2,000 lb Nylon Braid	1	20	2,540		26[9]		31[9]			42			64		59 61
	1	40	2,540		53		33		69	62 74		69	76		
	1	80	2,540		63	74 69[8]	81[4]								
2 inch 1,000 lb Nylon Ribbon	1	20	1,150		74		86 86			88			93		95[10]
	1	40	1,150		74	88	31	97		98[11]					
	1	80	1,150		94 96	100[12]									
1 inch 460 lb Nylon Ribbon	1	20	500		24		44			76			79		92
	1	40	500		30	61	64	90							
	1	80	500		84	99[12]									

1. Control value 6,040 pounds.
2. Contact time 23 seconds.
3. Contact time 47 seconds.
4. Contact time 11 seconds.
5. Contact time 37 seconds.
6. Contact time 17 seconds.
7. Contact time 9 seconds.
8. Contact time 7 seconds.
9. Control value 2,450 pounds.
10. Contact time 55 seconds.
11. Contact time 28 seconds.
12. Contact time 8 seconds.

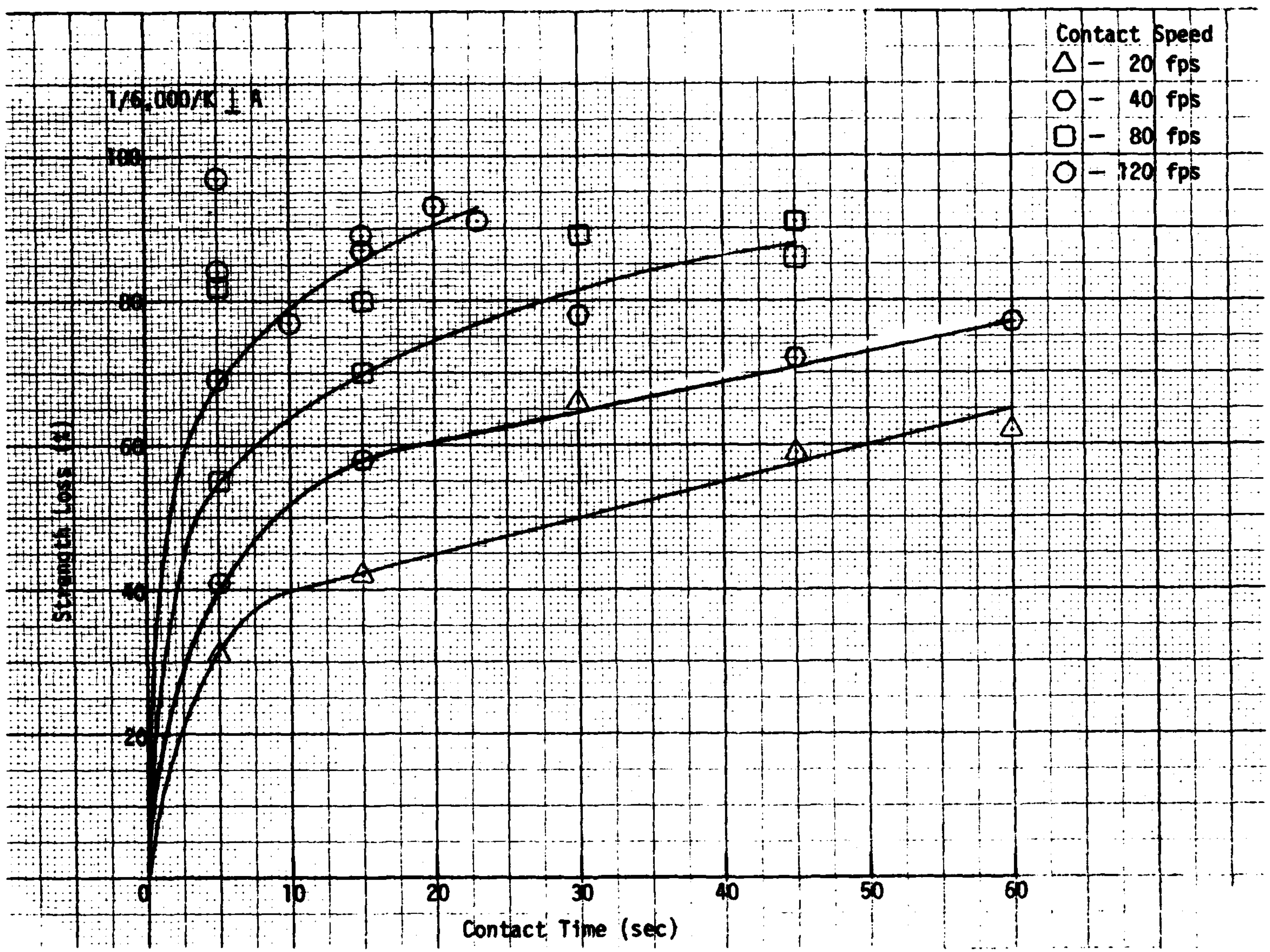


Figure 38. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Perpendicular Configuration Using a Contact Force of 2.5 Lb and Various Contact Speeds

B. <u>1 Inch 9,000 Lb Kevlar Webbing</u>

Figure 39 presents the results of abrasion of the 9,000 lb Kevlar webbing abraded at speeds of 20, 40, 80 and 120 fps using a contact force of 2.5 lb. No scorching was evident in any of the testing. Tensile breaks in this series were generally poor, occurring as a random popping of warp yarns. Variability of results was low, however. The shape of the curves is similar to those for the 6,000 lb Kevlar webbing. The curves exhibit good parallelism and the final slopes are similar to those for the 6,000 lb Kevlar webbing. A major difference is seen between the initial slopes of the two webbings. The initial slopes for the curves in Figure 39 are much lower than those in Figure 38, probably because the surface of the 9,000 lb webbing is much smoother, because of the construction, than the surface of the 6,000 lb webbing. This meant that the 9,000 lb webbing had a greater contact area (and therefore lower contact pressure) at the start of the test and underwent less of a change in surface characteristics than the 6,000 lb webbing as the test proceeded. As the test proceeded, however, after a finite amount of abrasion, both materials wore to similar surface characteristics and the abrasion resistance seemed to lose its construction dependency as indicated by the similarity between the final slopes for the two materials.

C. <u>2,000 Lb Kevlar Braid</u>

Figure 40 shows the results of testing with the Kevlar braid abraded at speeds of 20, 40 and 80 fps using a contact force of 1 lb. Variability in this series was generally high. No scorching was evident in any of the specimens. Tensile breaks were generally good. Transverse deflection of the specimen and the tendency of it to roll during the test may have caused the high variability. The curves in Figure 40 exhibit similar tendencies and show high strength losses for mild conditions. This may have been because in this configuration all of the yarns in the structure were in contact with the abradant at all times unlike the perpendicular Kevlar on Kevlar testing. As usual, the maximum rate of abrasion occurred in the initial portion of the test. In the curve corresponding to testing at 20 fps the linear portion of the curve indicated uniform surface characteristics and constant abrasion.

D. <u>1-3/4 Inch 4,000 Lb Kevlar Webbing</u>

Figure 41 shows the results of testing of 4,000 lb Kevlar webbing at speeds of 20, 40, 80 and 120 fps using a contact force of 1 lb. No scorching was evident in any of the testing. Tensile breaks in this series were generally poor, occurring as random popping of warp yarns. Control tests on this material also exhibited this type of failure. Variability of results was reasonably low, however. The curves in Figure 41 are somewhat unusual in that they are clumped closely together. This indicated less of a speed dependency than was found for the heavy webbings. Strength losses were high, especially in the initial portion of the curve. A fairly sharp change in rate of abrasion occurred in the curves corresponding to testing at 20 and 40 fps. This again indicated a wearing of the fabric knuckles. These two curves also exhibit good parallelism and all four of the curves demonstrate similar relationships between strength loss and contact time and speed.

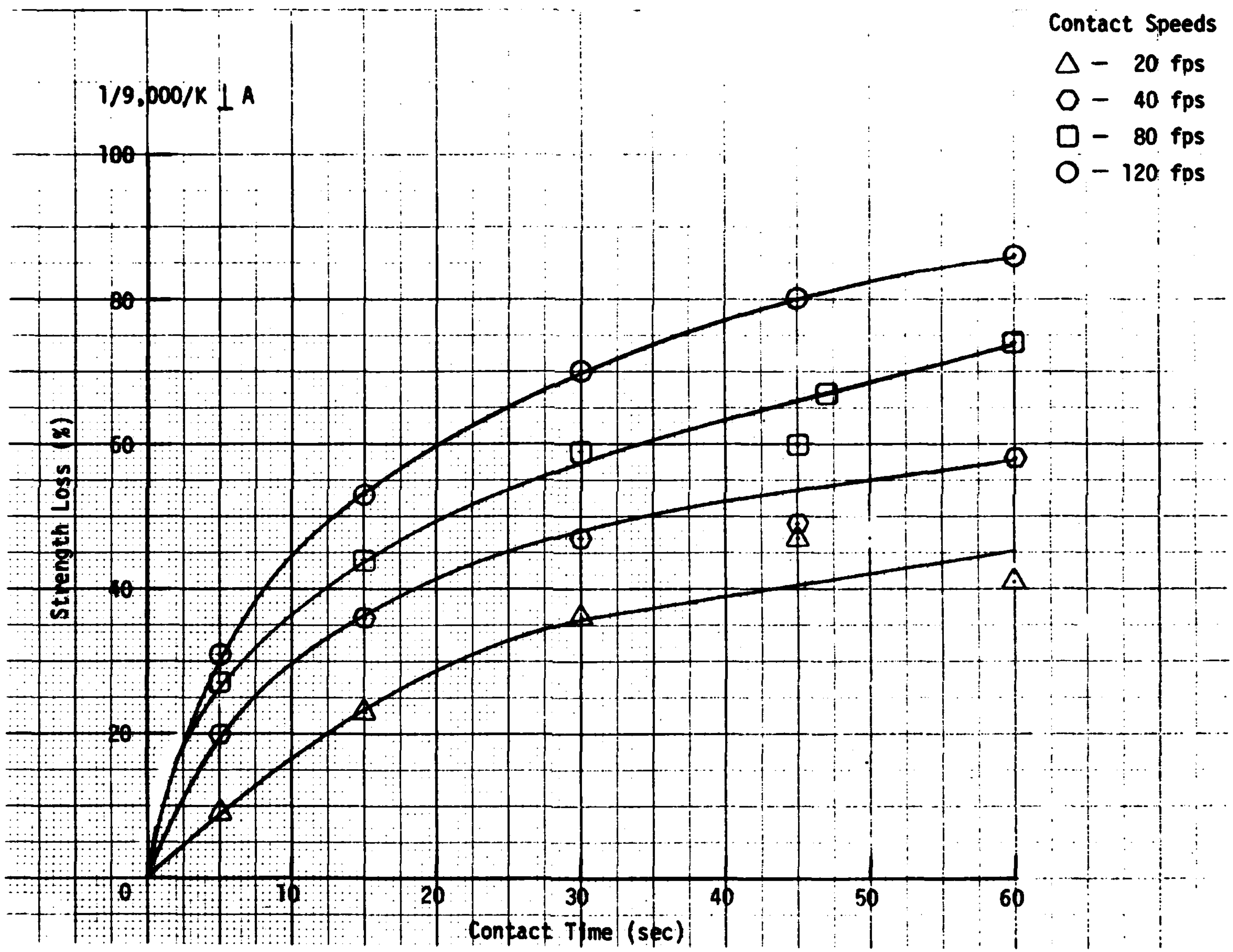


Figure 39. Strength Loss as a Function of Contact Time for a 1 Inch 9,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Perpendicular Configuration Using a Contact Force of 2.5 Lb and Various Contact Speeds

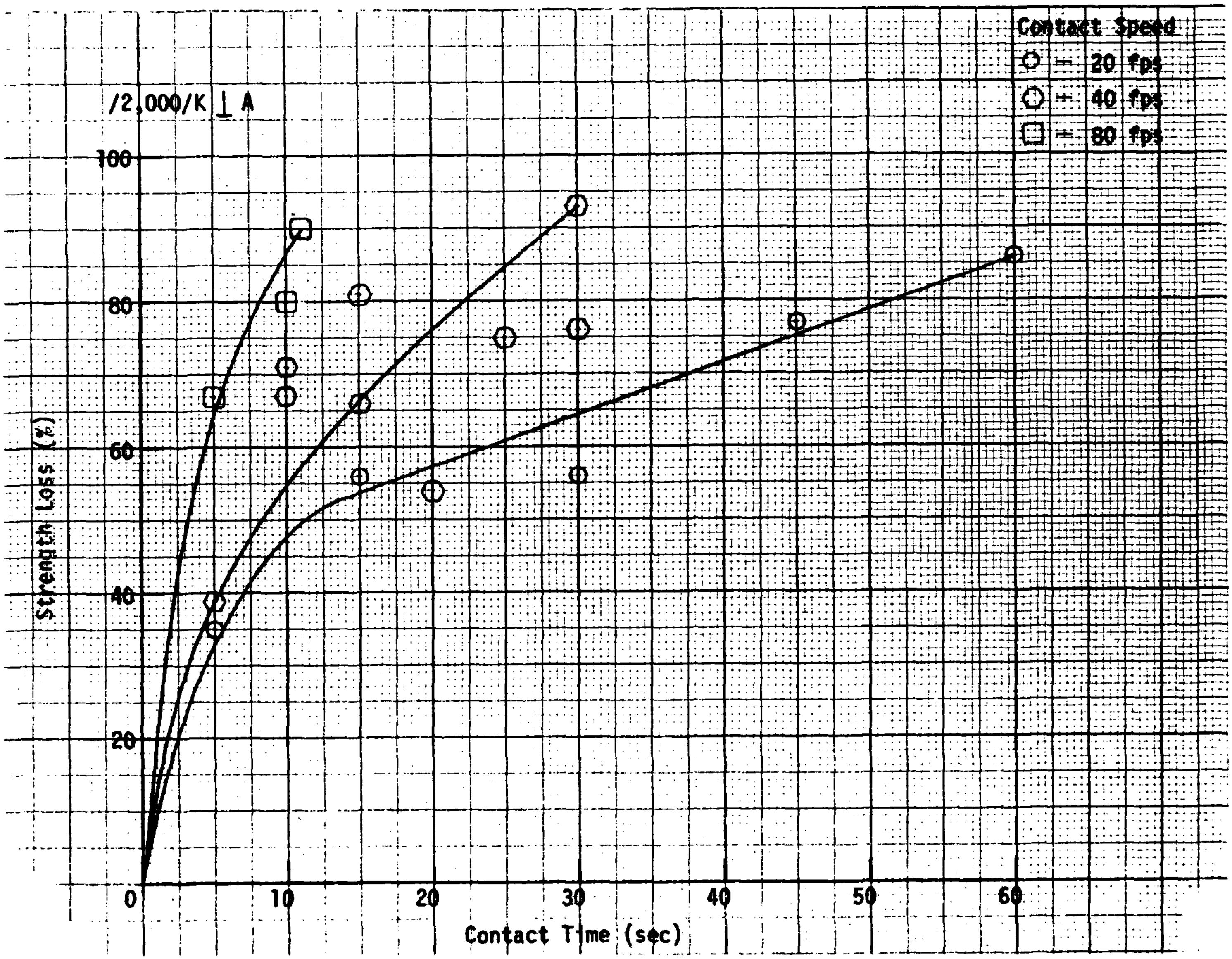


Figure 40. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

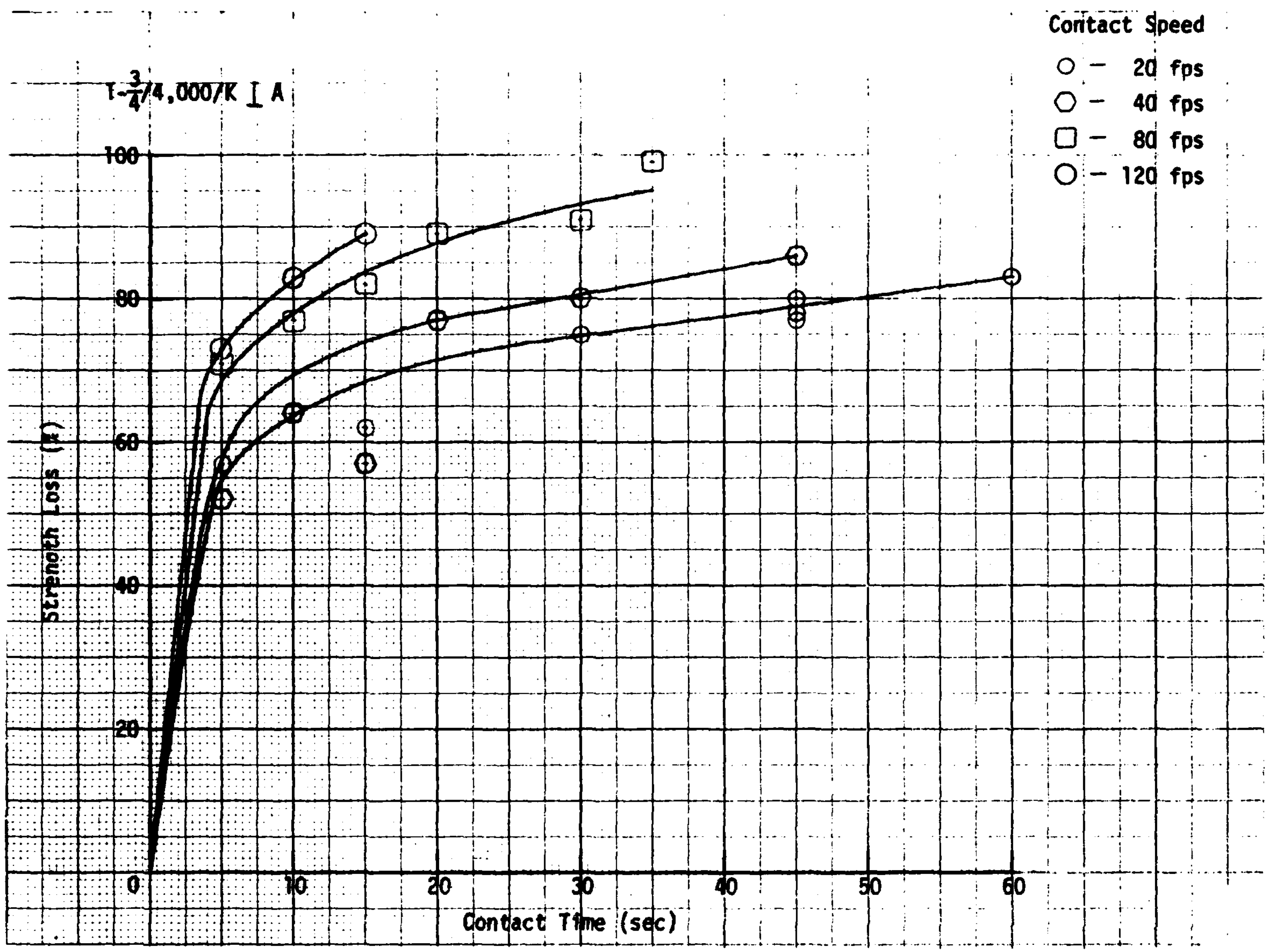


Figure 41. Strength Loss as a Function of Contact Time for a 1-3/4 Inch 4,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

E. 2 Inch 1,000 Lb Kevlar Ribbon

Figure 42 shows the results of testing with the 1,000 lb Kevlar ribbon abraded at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No scorching was evident in any of the specimens. Tensile breaks were poor, most occurring as random popping of warp yarns due to the high strength loss. Control failures were good, however. Variability in results was low even though the abrasion in this series was very non-uniform for reasons mentioned previously. This test configuration did not seem to work well with this material as most of the abrasion occurred at the edges of the abraded area. The curves in Figure 42 are similar in nature to those in Figure 41 for the 4,000 lb Kevlar webbing. Strength losses were extremely high in the initial portion of the test. There was a sharp change in the rate of abrasion which occurred shortly after the start of the test. Strength losses in general were very high and the closeness of the curves to one another indicated a minor speed effect.

F. 2 Inch 480 Lb Kevlar Ribbon

Test results for this ribbon are given in Table 8. It was only possible to test this material at a speed of 20 fps using a contact force of 1 lb. Even at these mild conditions, contact time was limited to 10 seconds. Abrasion was very non-uniform and no scorching was seen. This testing was not very meaningful because of limitations on conditions and non-uniform abrasion.

G. 1 Inch 6,000 Lb Nylon Webbing

Figure 43 shows the results of testing the 6,000 lb nylon webbing at speeds of 20, 40, 80 and 120 fps using a contact force of 2.5 lb. No melting was evident in the specimens tested. Tensile breaks were generally poor occurring as tears. Variabilty was low. The curves in Figure 43 are similar in shape to those for the Kevlar webbings. The maximum rate of abrasion is seen as a high slope in the initial portion of the curves. The linear portion of the curves again indicates a uniform rate of abrasion and is also similar in slope to what was found for the Kevlar webbings. These materials were all abraded under identical conditions. Both 6,000 lb webbings exhibit similar relationships between strength loss and contact time and speed in the initial portion of the curves. This initial high slope was attributed to the uneven surface and low initial contact area for the 6,000 lb Kevlar webbing. The 6,000 lb nylon webbing has a much smoother surface, however, more closely resembling the 9,000 lb Kevlar webbing. However, the initial portion of the curves in Figure 43 does not resemble those for the 9,000 lb Kevlar webbing. In general, the strength losses for the two 6,000 lb webbings are very similar at the two speeds. A more in-depth comparison is included later in this section.

H. 2,000 Lb Nylon Braid

Figure 44 shows the results of testing of the nylon braid at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No melting was seen in any of the test specimens. Tensile breaks in this series were good. Variability of results in this series was generally low. The curves in Figure 44 are similar in shape to what has been found in other materials for this configuration. The initial portion of the curve indicate high abrasion with the transition to a lower, more uniform rate of abrasion as the test proceeded.

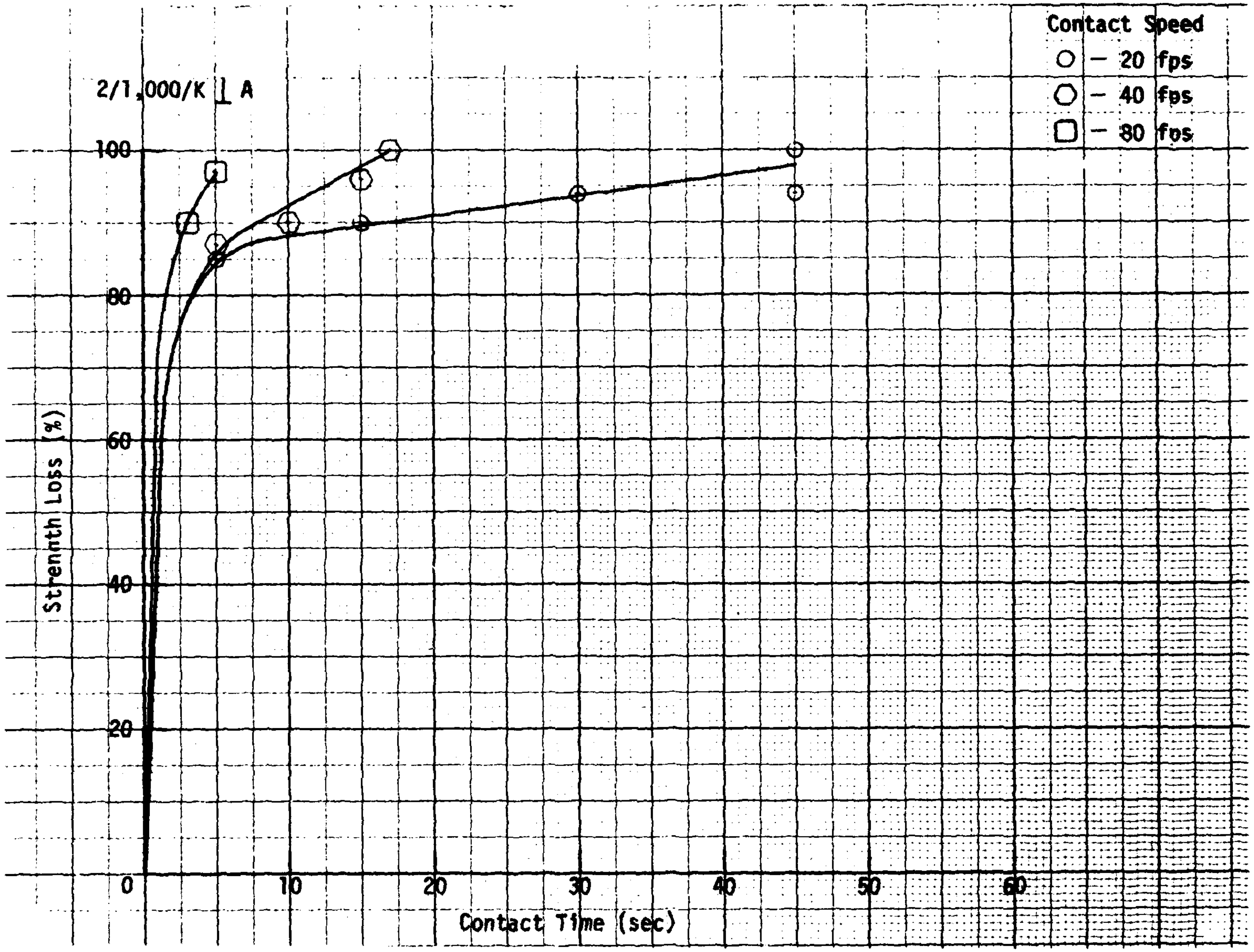


Figure 42. Strength Loss as a Function of Contact Time for a 2 Inch 1,000 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

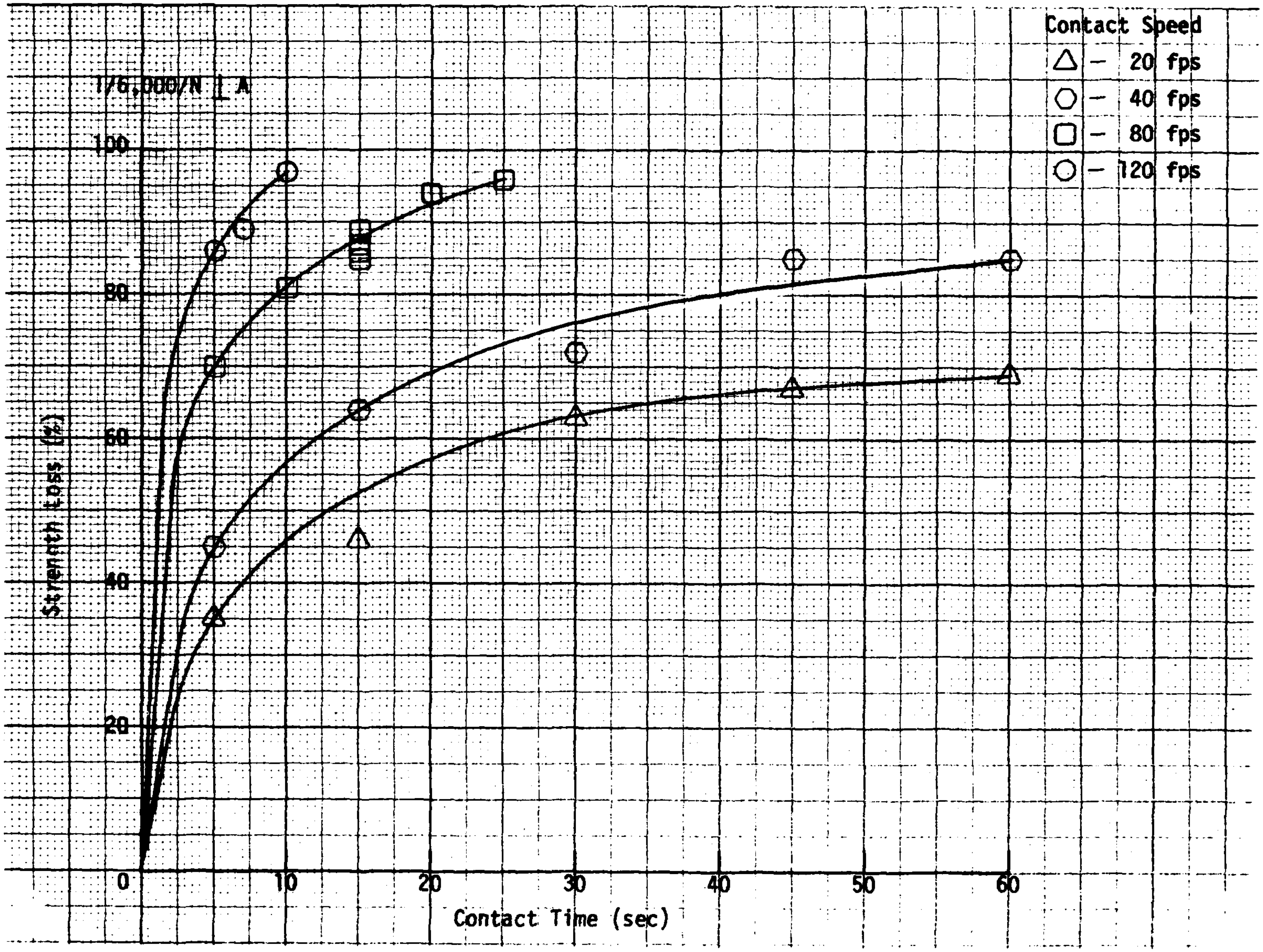


Figure 43. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Abrasive Perpendicular Configuration Using a Contact Force of 2.5 Lb and Various Contact Speeds

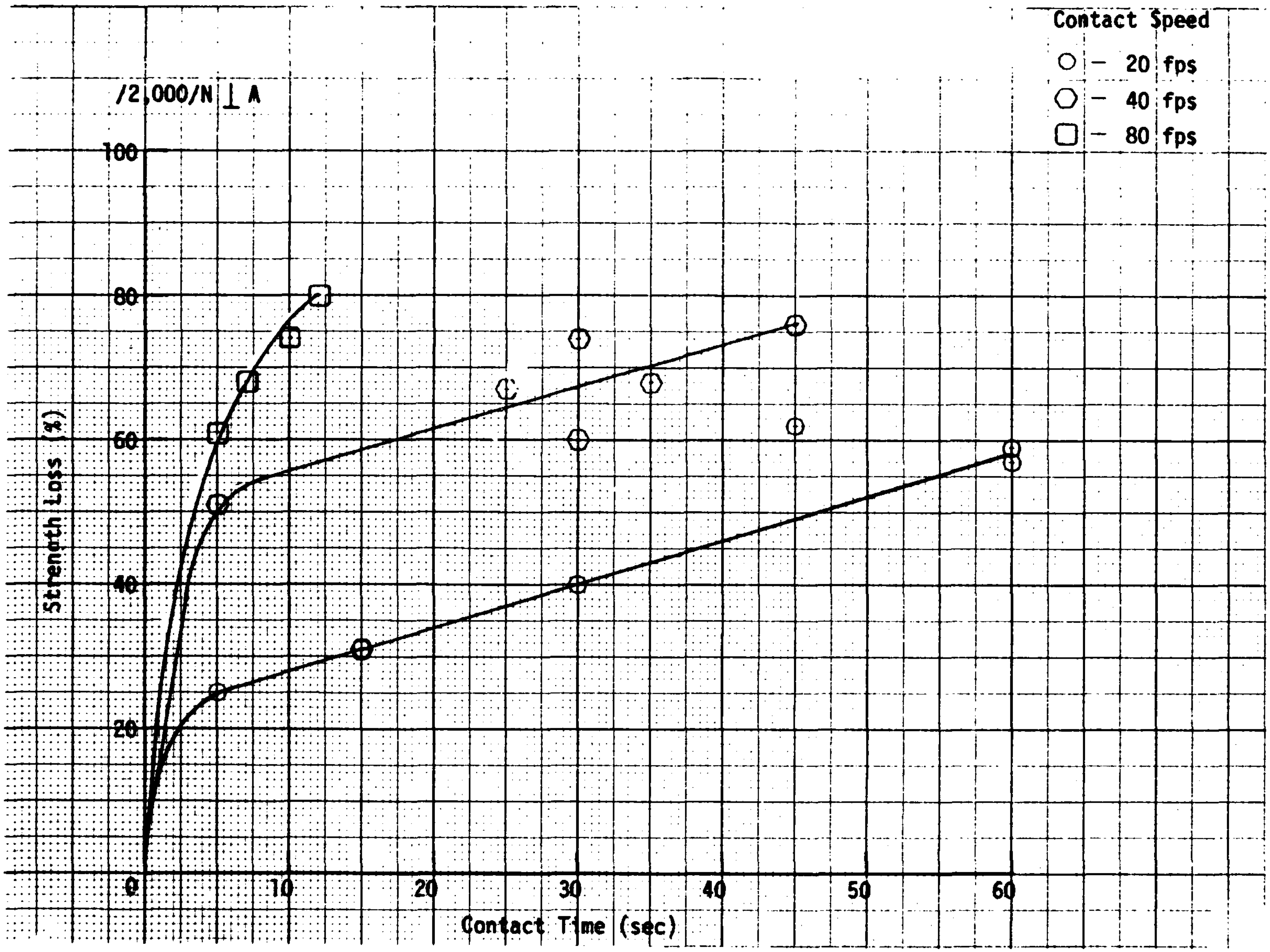


Figure 44. Strength Loss as a Function of Contact Time for a 2,000 Lb Nylon Braid Abraded in the Nylon on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

I. 2 Inch 1,000 Lb Nylon Ribbon

Figure 45 shows the results of testing of the 1,000 lb nylon ribbon abraded at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No melting was evident in this test series and abrasion was, again, very nonuniform with the maximum wear occurring at the edge of the abraded area. Variability in this series was generally low except for testing at 40 fps and long contact times. Tensile breaks in this series were poor, occurring as random popping of warp yarns. The curves in Figure 45 are similar to what had been seen previously with other materials and exhibit good parallelism. The curves for the nylon ribbon have a slightly lower slope initially and a more gradual transition to the linear portion of the curve than do the Kevlar materials.

J. 2 Inch 460 Lb Nylon Ribbon

Figure 46 shows the results of testing with the 460 lb nylon ribbon abraded at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No melting was evident in any of the specimens. Tensile breaks in this series were poor, occurring as tears. Variability of results was reasonably low, however. The curves in Figure 46 are somewhat unexpected. Strength losses are generally low. There appeared to be a large speed effect compared to the other lightweight materials (both nylon and Kevlar). Initial slopes were also very low when compared to other lightweight materials. The most unexpected result of this testing is the superior performance of this ribbon over the 1,000 lb nylon ribbon abraded under the same conditions. Comparison of Figures 45 and 46 shows a significant difference between the two materials. Both ribbons are a twill weave construction. However, as mentioned previously, the 1,000 lb ribbon has more than twice the number of warp yarns of the same denier as the 460 lb ribbon and a lower pick count. The result is a lower twill line angle and burial of the filling yarns within the structure of the 1,000 lb ribbon. The 460 lb ribbon is a much looser construction. Tensioning this ribbon under a microscope revealed that the warp yarns were straightened to the point where the surface of both warp and fill were in the same plane on the surface of the fabric. Therefore, the abrasion was shared somewhat by both warp and fill, more so in this perpendicular testing than in the parallel testing because of higher specimen tension. However, only abrasion of the warp yarns directly affected the strength loss measured in normal tensile testing. All abrasive damage for the 1,000 lb ribbon was sustained by the warp. This could have caused the significant difference in abrasion resistance.

K. Kevlar/Nylon Comparison

1. Webbings

Figures 47 through 50 present the results of abrasion of the two 6,000 lb webbings and the 9,000 lb webbing at speeds of 20, 40, 80 and 120 fps respectively. All tests were conducted with a contact force of 2.5 lb. Again, as in the parallel on abrasive surface testing, the 9,000 lb Kevlar webbing performed the best at all speeds. Also, at all speeds, the 6,000 lb Kevlar webbing exhibited better abrasion resistance than the 6,000 lb nylon webbing. At 20 fps, the abrasion resistance of all three was very similar. As the test speed increased, the 9,000 lb webbing exhibited better abrasion resistance relative to the 6,000 lb Kevlar webbing and the nylon webbing

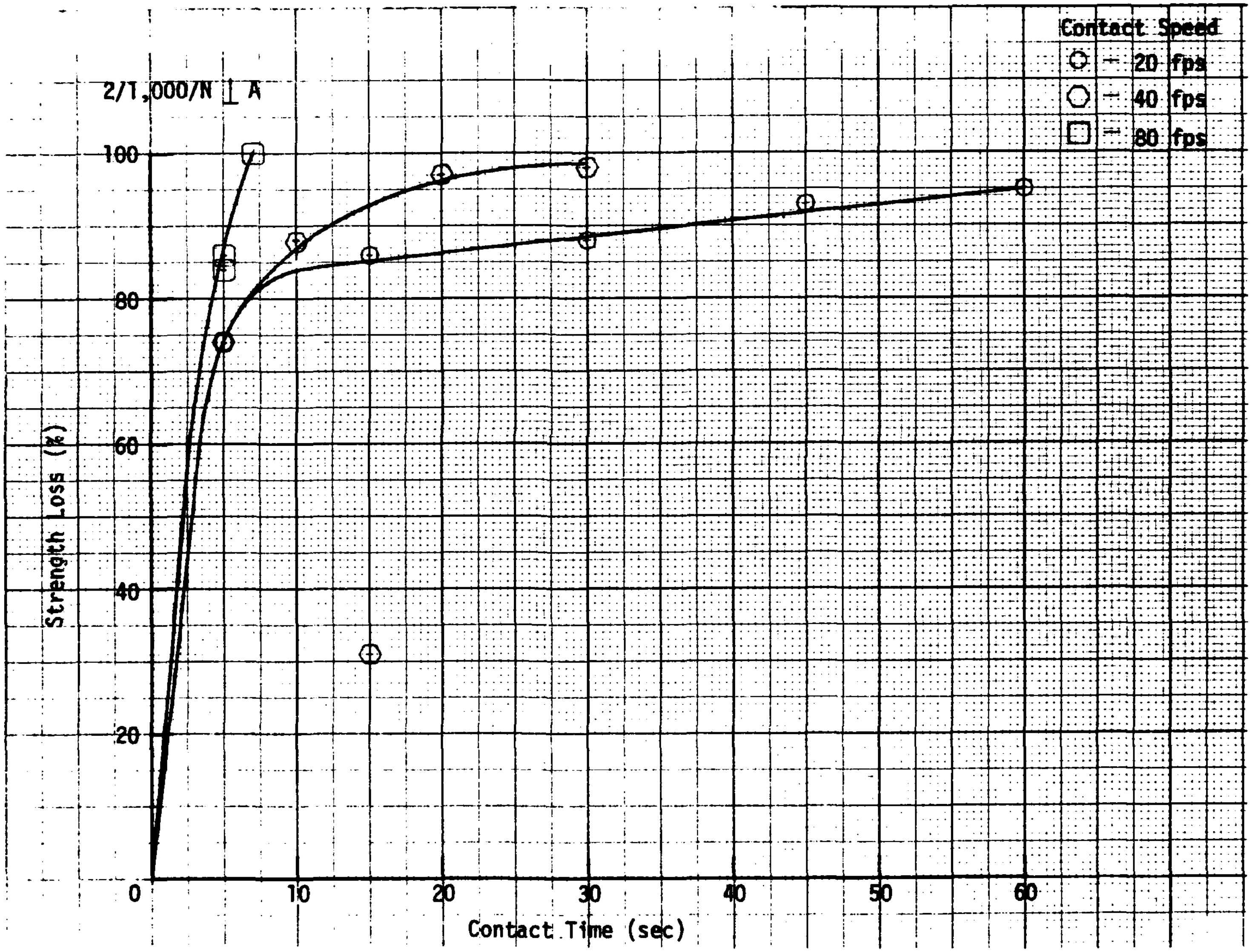


Figure 45. Strength Loss as a Function of Contact Time for a 2 Inch 1,000 Lb Nylon Ribbon Abraded in the Nylon on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

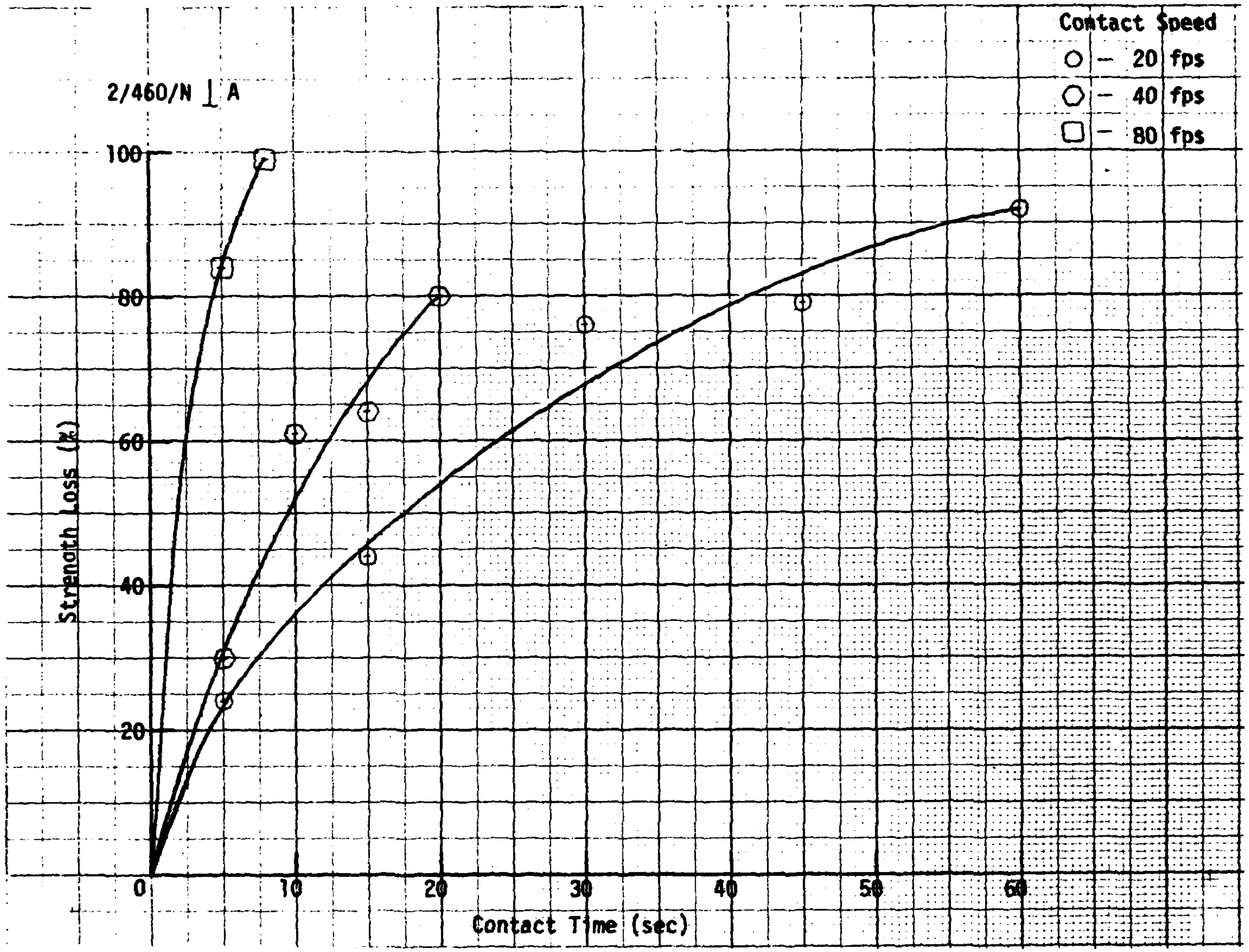


Figure 46. Strength Loss as a Function of Contact Time for a 2 Inch 460 Lb Nylon Ribbon Abraded in the Nylon on Abrasive Perpendicular Configuration Using a Contact Force of 1 Lb and Various Contact Speeds

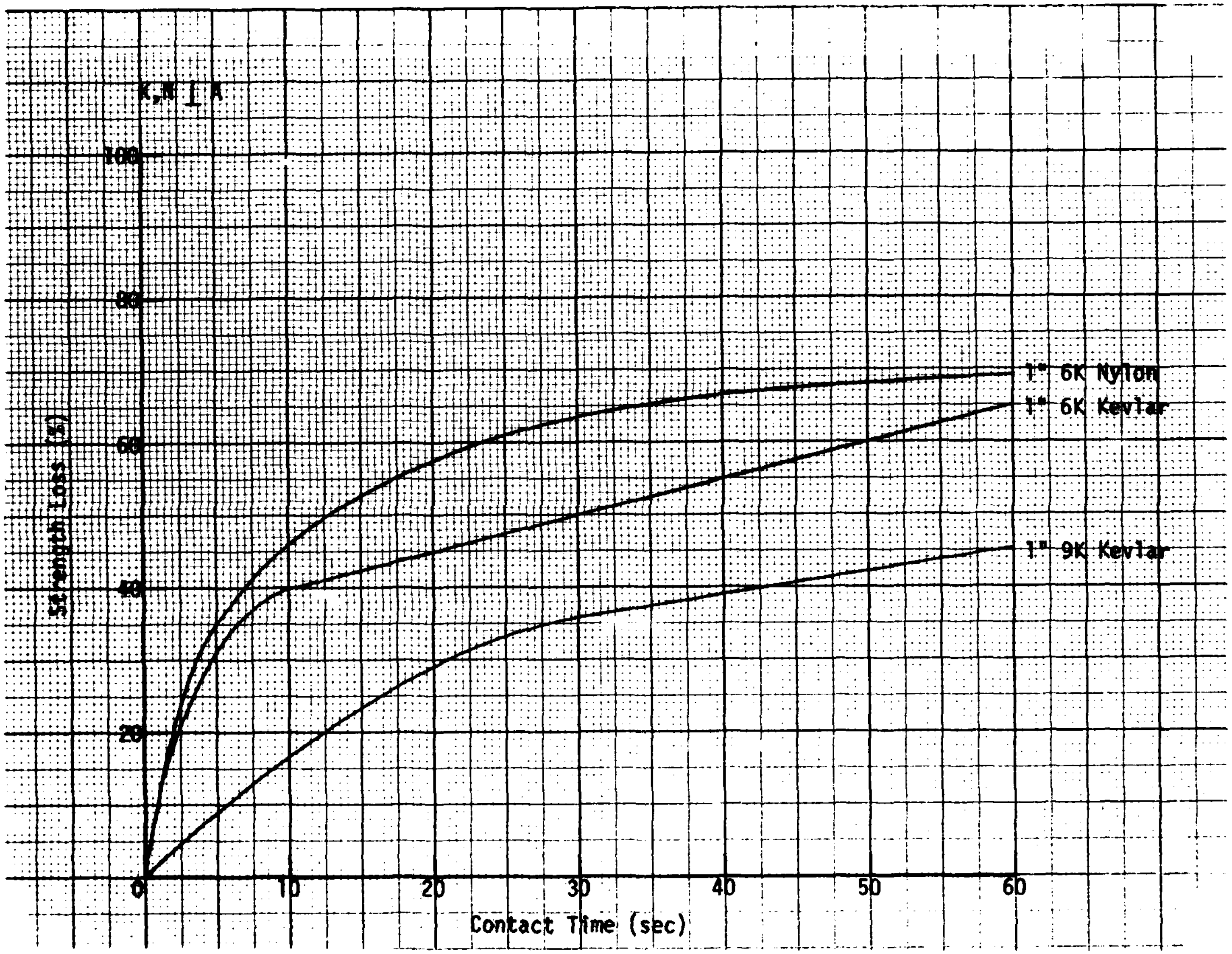


Figure 47. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 20 fps Using a Contact Force of 2.5 Lb

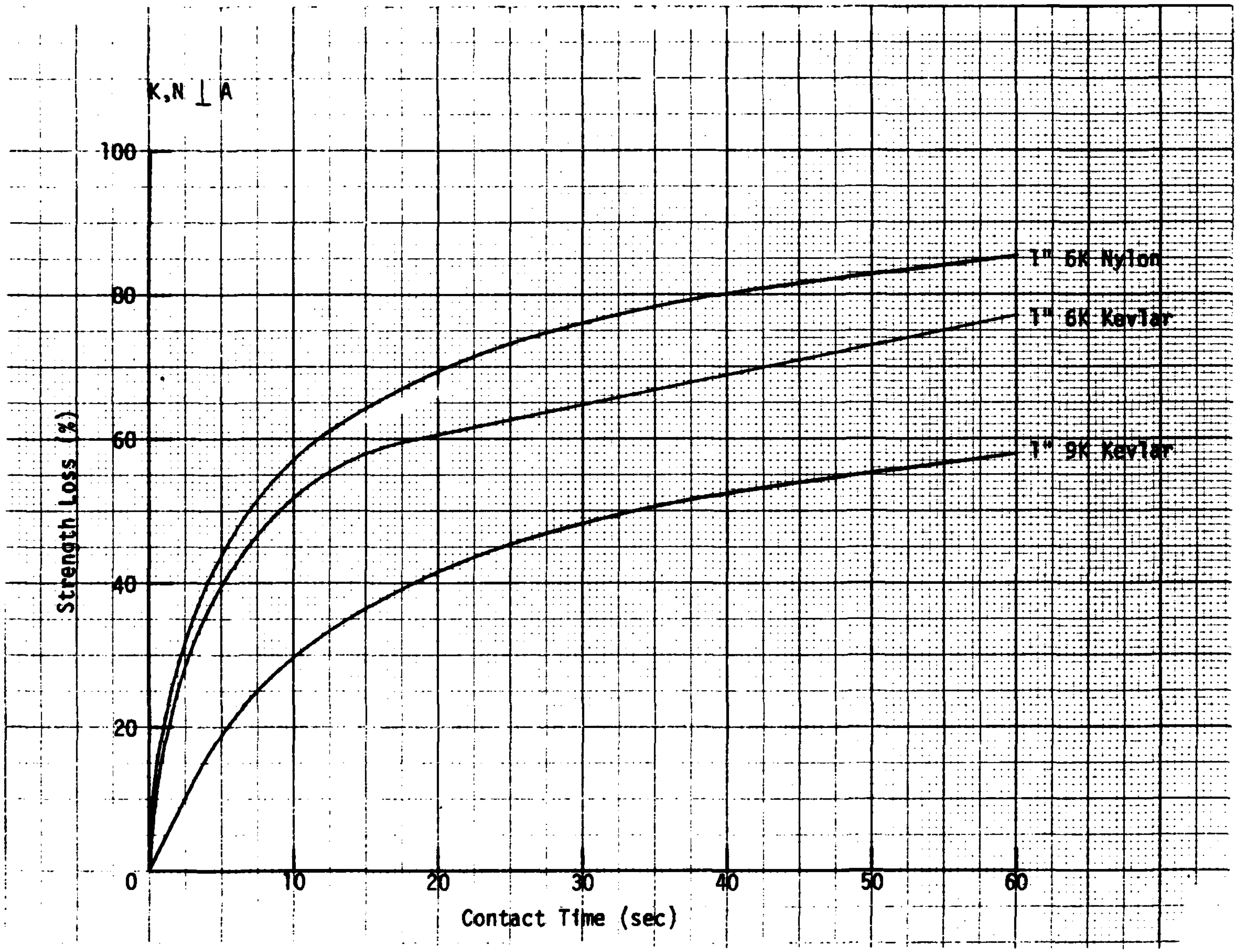


Figure 48. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 40 fps Using a Contact Force of 2.5 Lb

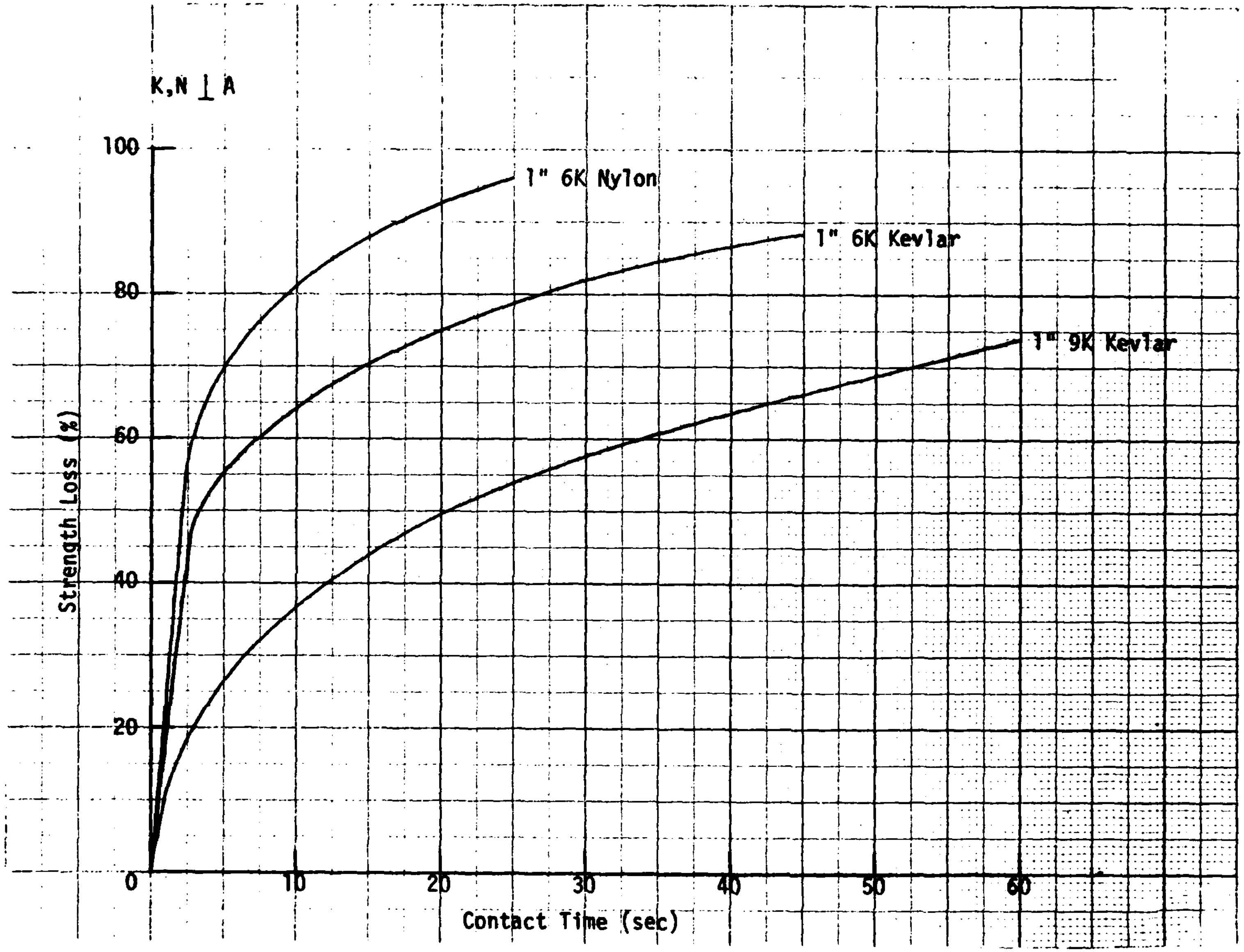


Figure 49. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 80 fps Using a Contact Force of 2.5 Lb

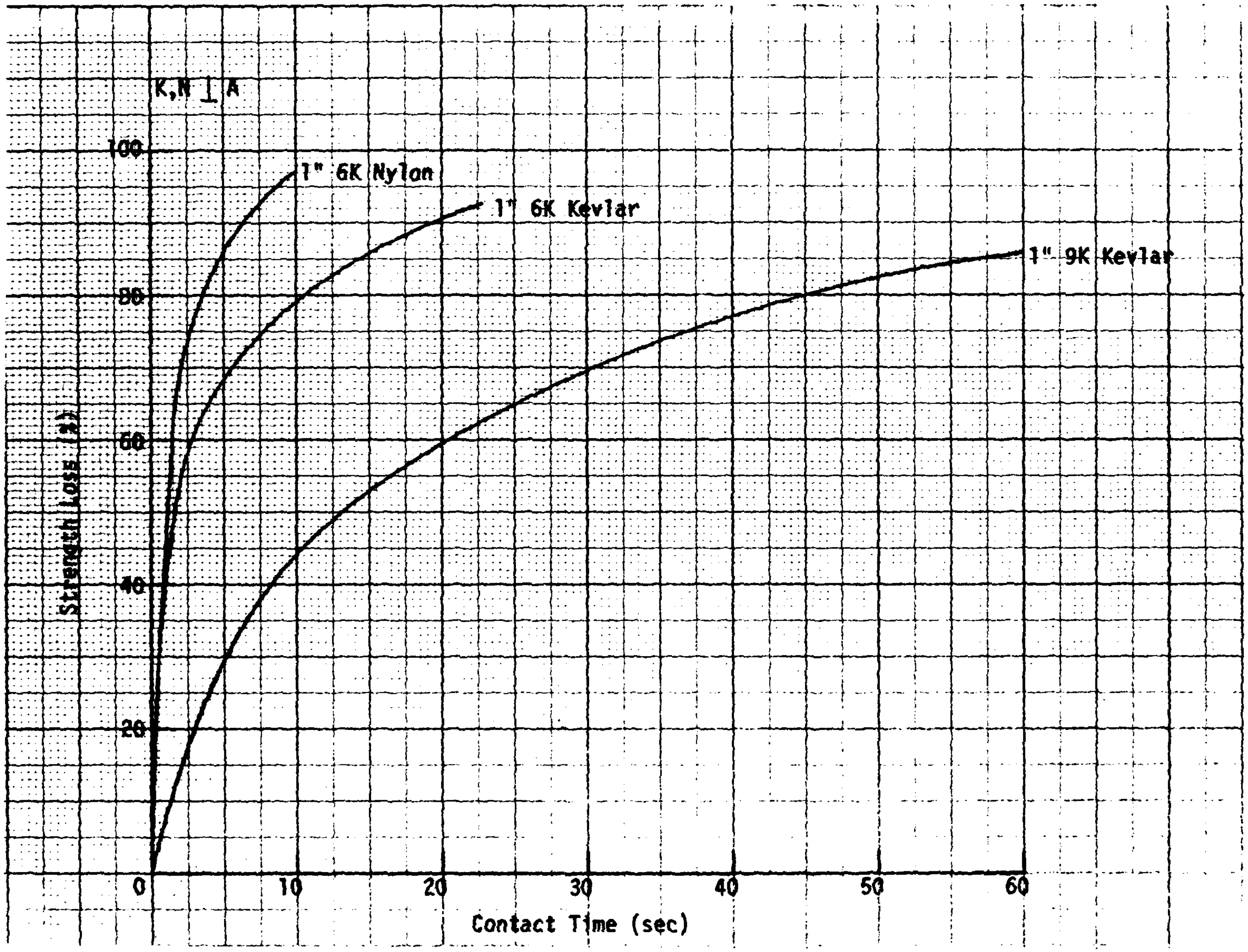


Figure 50. Strength Loss as a Function of Contact Time for Three Webbings Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 120 fps Using a Contact Force of 2.5 Lb

exhibited worse abrasion resistance relative to the 6,000 lb Kevlar webbing. However, the effect of speed on the nylon webbing in this abrasion configuration was not nearly as great as it was in the nylon on nylon abrasion configuration. Moreover, there were no obvious thermal effects. The curves for all three materials are similarly shaped. The lack of a drastic change in slope in the curves may have been due to the high specimen tension used in this testing. The 6,000 lb Kevlar webbing had shown a sharp change in abrasion in parallel testing (Figures 6 and 19) but not in the Kevlar perpendicular testing (Figure 14) where high tension was also used. Here again, the Kevlar webbings demonstrated superior high speed abrasion resistance over the nylon webbing, compared on the basis of either equal strength or similar weight, thickness, construction and surface characteristics.

2. Braids

Figures 51, 52 and 53 compare the results of testing of the braids in this configuration at speeds of 20, 40 and 80 fps. In all three figures the nylon braid showed superior abrasion resistance over the Kevlar braid. As in the previous comparison between webbings, the abrasion resistance of the Kevlar materials improved with increasing test speed relative to the nylon braid. In Figure 51 (testing at 20 fps) the curves for the two materials were similar in shape with the Kevlar sustaining about 20% greater strength loss than the nylon in this testing. In Figure 53 (testing at 80 fps) the curves for the two materials were similar in shape again. However, strength losses here were much more similar with the maximum difference being 10% at the maximum contact time. At 40 fps (Figure 52) the curves were dissimilar in shape and the Kevlar braid actually sustained less abrasive damage than the nylon in the first 10 seconds. However, exact definition of the shape of these curves in this region was often difficult. Comparison of Kevlar and nylon braided materials on a strength basis, therefore indicated the superior performance of the nylon material. However, speed effects evident in these results indicated the possible reversal of this trend if higher speeds were used (with lower loads). Also, although contact force used in this testing was equal for the two materials, contact pressure was not equal because of differences in braid dimensions. The sensitivity of the nylon braid to contact force in this test configuration was not investigated. However, indications from nylon on nylon testing were that the effects of contact force on abrasion were high and so could have caused a substantial change in the measured abrasion resistance in this configuration if the contact force had been increased to equalize contact pressure for the two materials. No obvious thermal effects were observed.

3. Ribbons

Figures 54, 55 and 56 compare the results of testing four lightweight structures in this configuration at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No obvious thermal effects were observed. A surprising result here was the excellent performance of the 460 lb nylon ribbon which even outperformed the 4,000 lb Kevlar webbing under many conditions. However, the performance of the 4,000 lb webbing improved relative to the 460 lb ribbon with increasing contact speed. The 1,000 lb ribbons demonstrated almost identical abrasion resistance at all three speeds Close inspection of the abraded specimens revealed that only the 1,000 lb nylon ribbon did not sustain abrasive damage in the filling yarns. Furthermore, the 460 lb ribbon showed, by far, the most abrasive damage in the filling yarns of all four structures. In this ribbon, there appeared to be more abrasive damage to the filling than

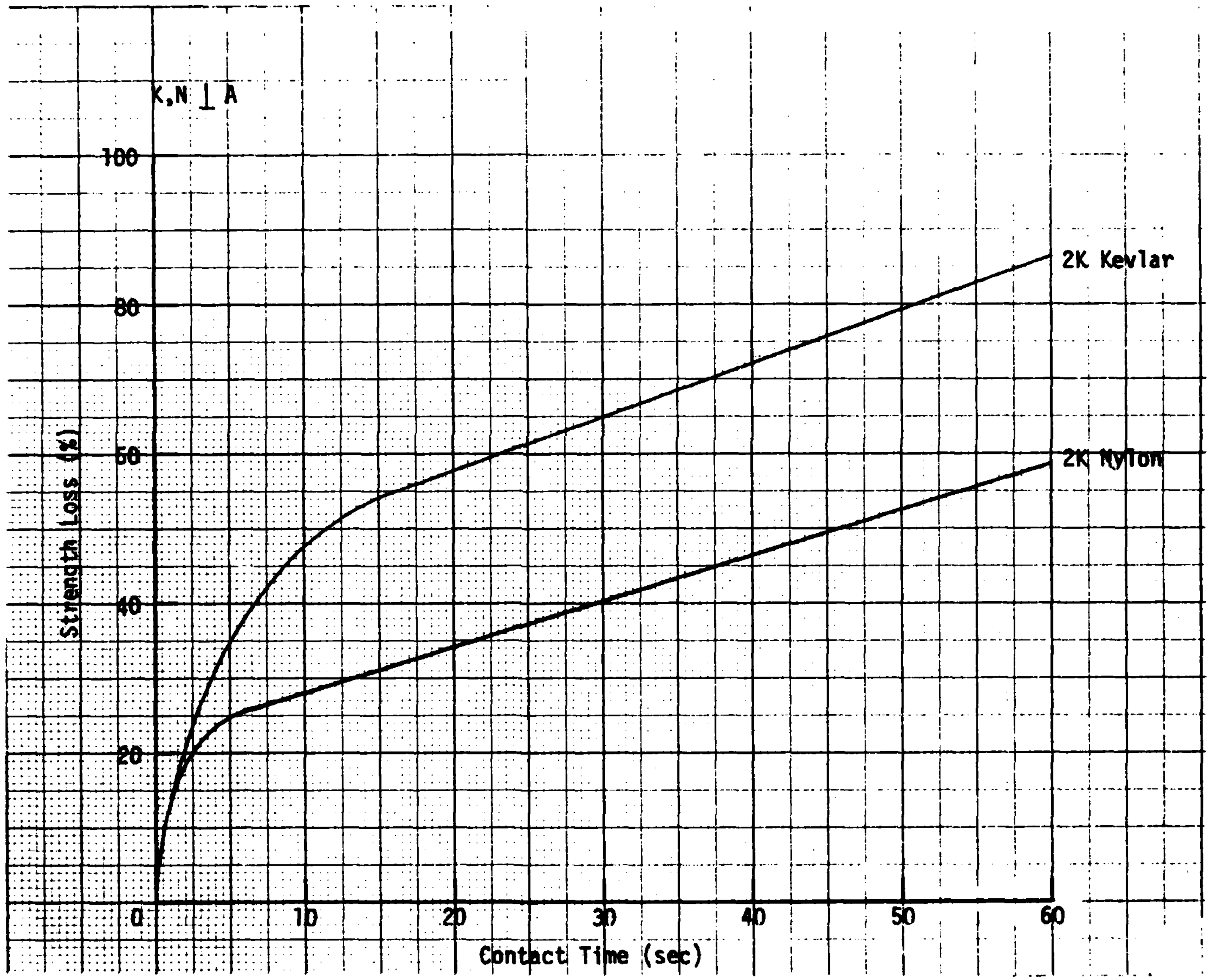


Figure 51. Strength Loss as a Function of Contact Time for Two Braids Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 20 fps Using a Contact Force of 1 Lb

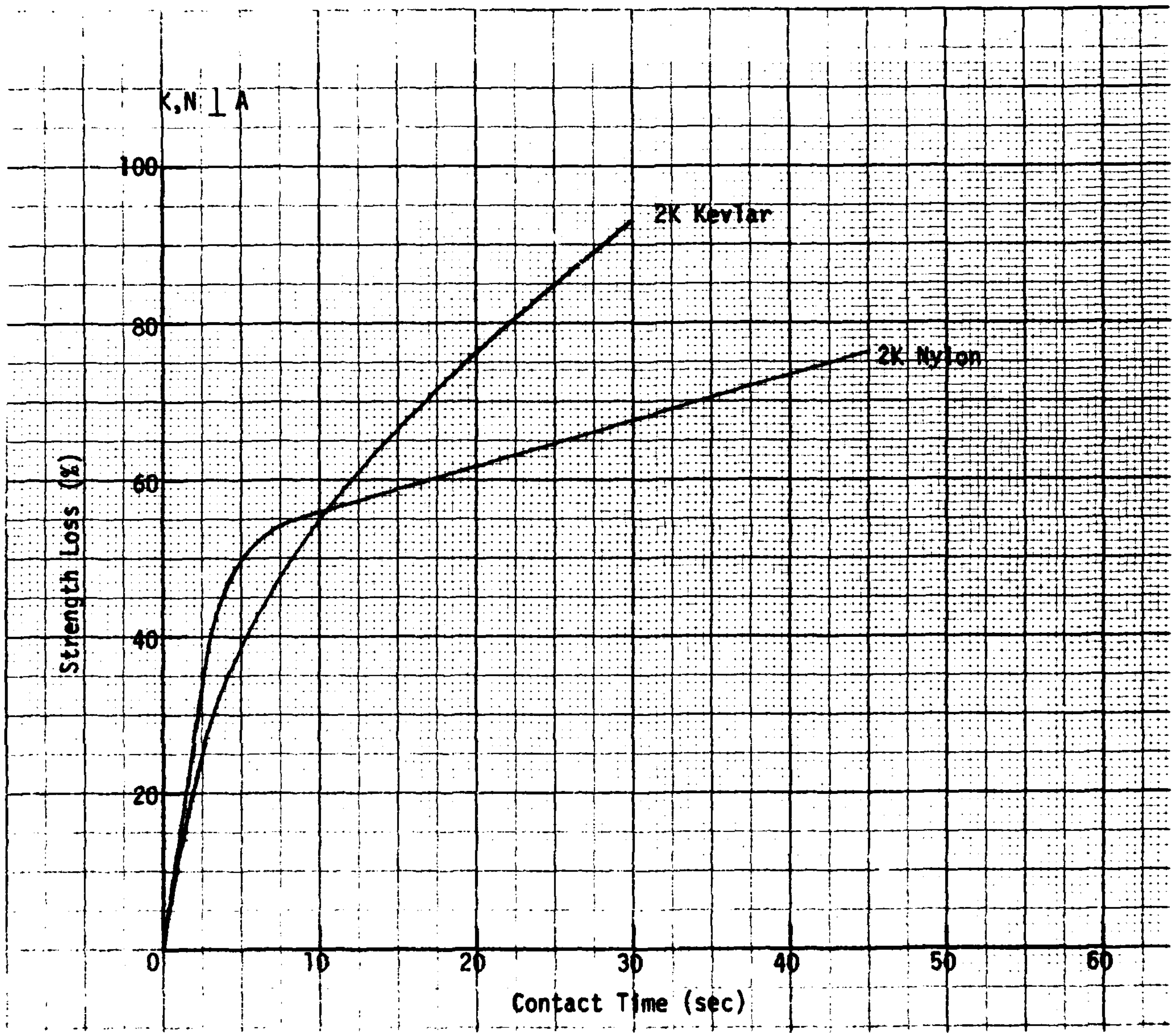


Figure 52. Strength Loss as a Function of Contact Time for Two Braids Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 40 fps Using a Contact Force of 1 Lb

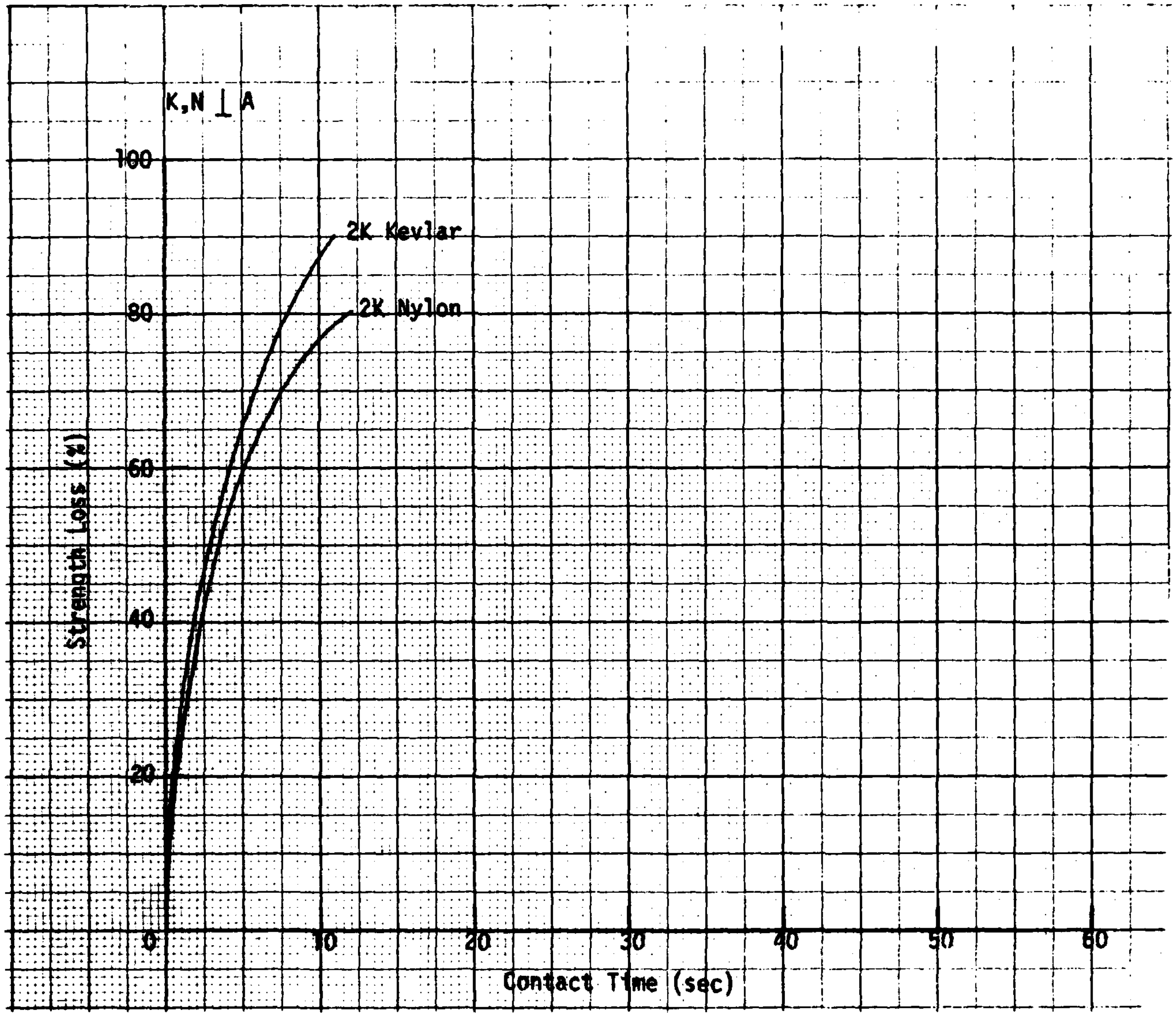


Figure 53. Strength Loss as a Function of Contact Time for Two Braids Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 80 fps Using a Contact Force of 1 Lb

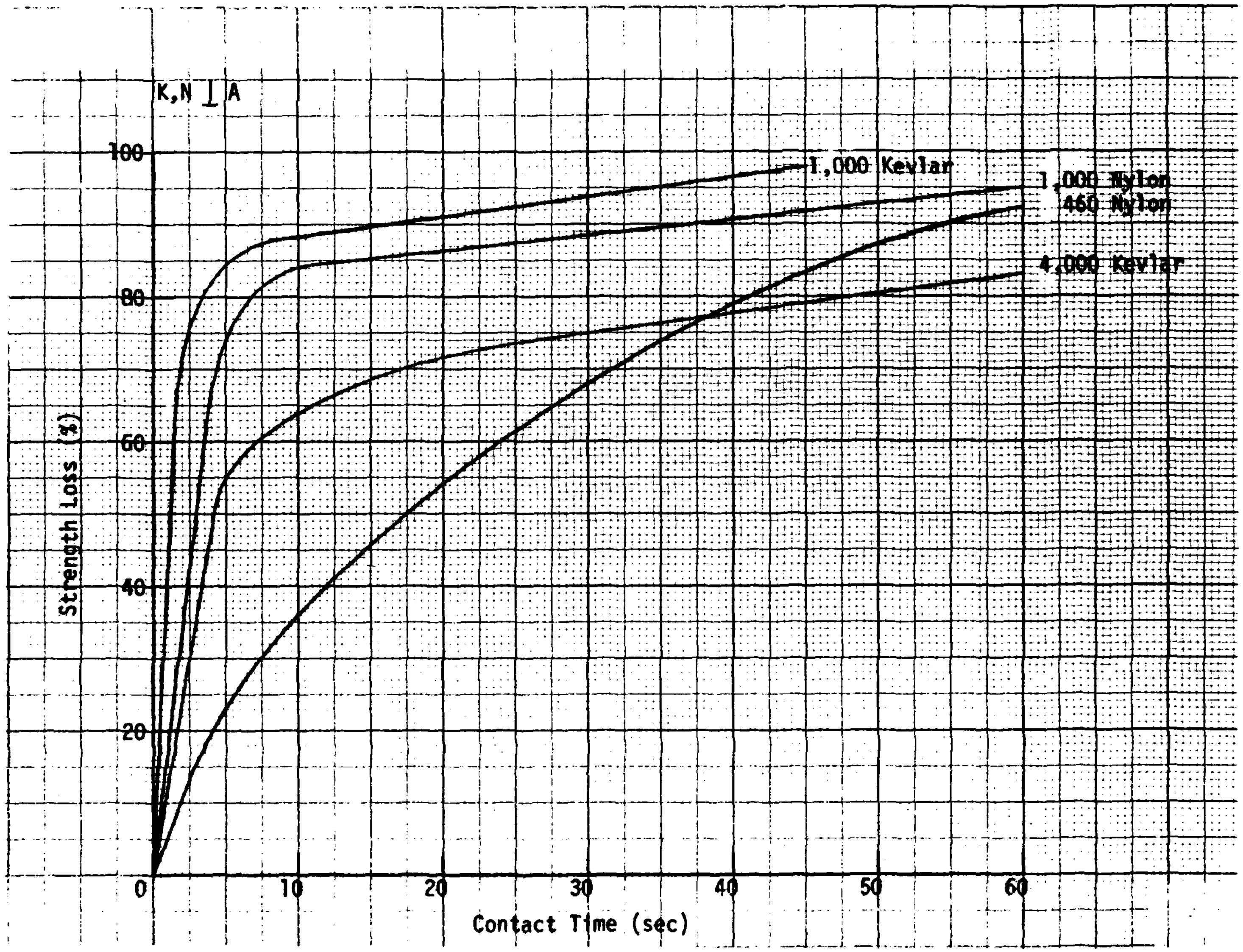


Figure 54. Strength Loss as a Function of Contact Time for Four Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 20 fps Using a Contact Force of 1 Lb

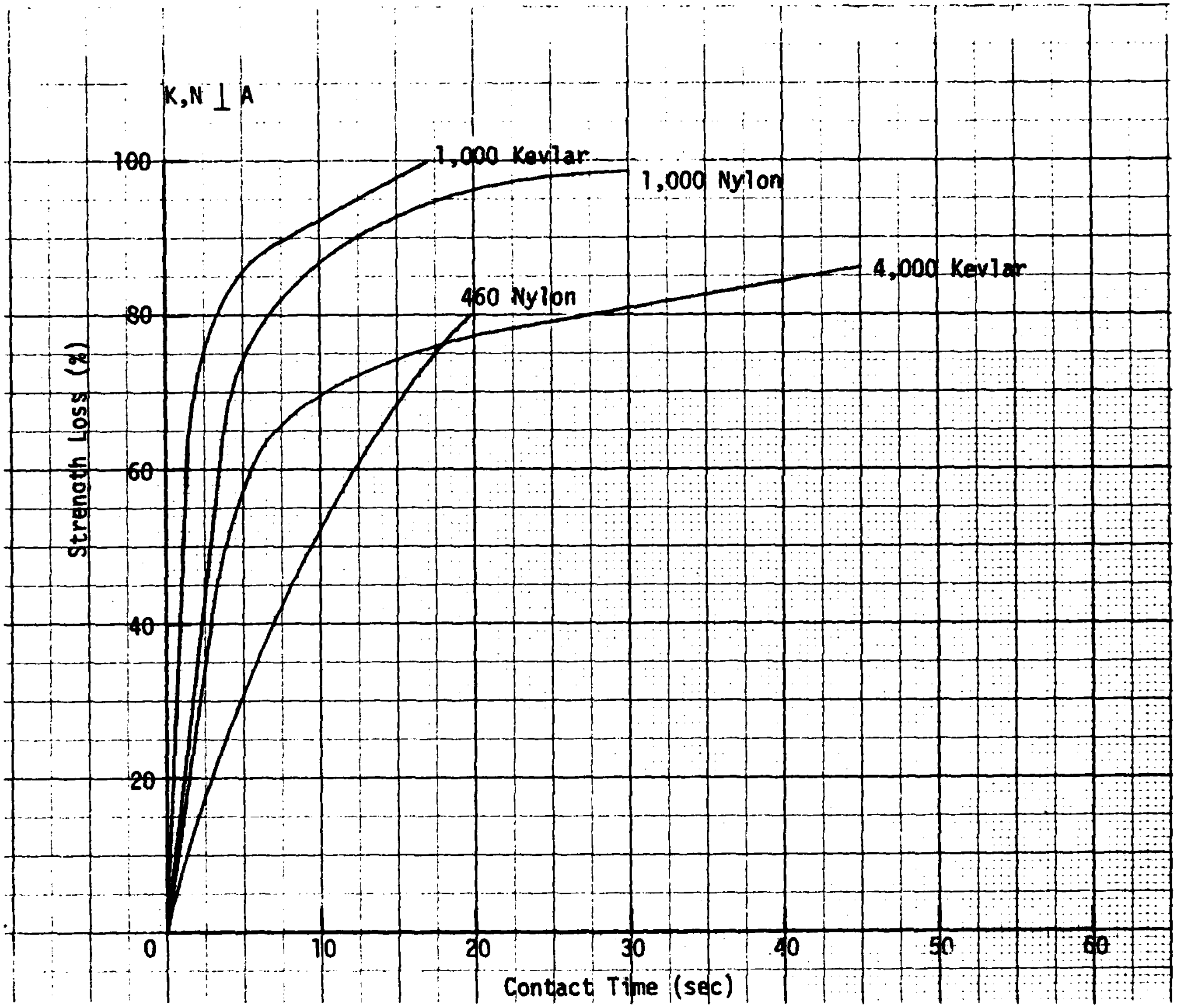


Figure 55. Strength Loss as a Function of Contact Time for Four Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 40 fps Using a Contact Force of 1 Lb

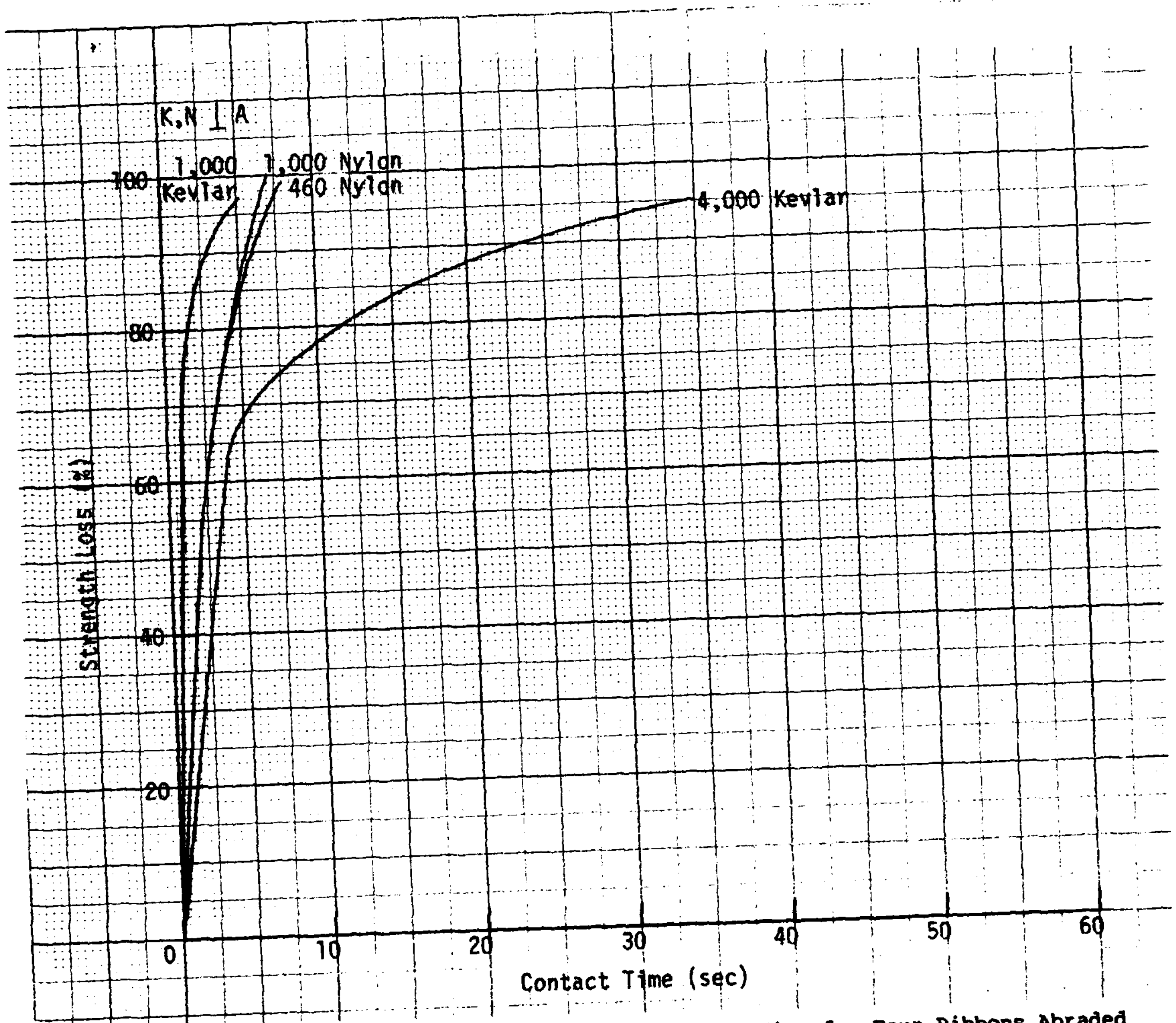


Figure 56. Strength Loss as a Function of Contact Time for Four Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at 80 fps Using a Contact Force of 1 Lb

the warp, especially at relatively mild test conditions before the filling had been severely abraded. The abrasion of the filling aided in the preservation of the structure strength since it must obviously have sustained some portion of the contact force, acted to increase the effective contact area and yet contributed nominally nothing to the strength, or more importantly strength loss, of the structure. The interaction of the filling in this test configuration as opposed to the parallel configuration was most likely due to the substantially higher specimen tension used in this configuration. This high specimen tension served to reduce warp crimp and increase filling yarn crimp. The low strength and loose construction of the 460 lb nylon ribbon was probably the reason for the substantial interaction of the filling yarns due to high yarn crimp. The construction of the 1,000 lb ribbon resulted in burial of the filling yarns with essentially no crimp and tensioning of this structure did not bring the filling yarns to the surface. Therefore, all of the abrasive damage in this structure was incurred by the load bearing warp yarns.

Comparisons between these ribbon materials are difficult to make due to constructional differences. On the basis of strength, it would appear that nylon again exhibited abrasion resistance which was superior to that of the Kevlar materials. This was evident from comparisons between the two 1,000 lb ribbons and the two nominal 500 lb ribbons even though strength loss mechanisms varied greatly from one material to the other. On the basis of weight and thickness, the 4,000 lb Kevlar webbing performed better than the 1,000 lb nylon ribbon inclusive of structural effects. However, the significance of these structural effects is evidenced by the generally superior performance of the lighter, thinner, and weaker 460 lb nylon ribbon over these two constructions.

SECTION IX

EFFECTS OF SPECIMEN TENSION

Many of the curves associated with testing at 160 fps and in some cases 240 fps were dissimilar in shape to curves associated with testing at lower speeds. It was believed that this could have been due to a change in tension in the abraded specimen resulting from a change in wheel diameter in going from a speed of 160 fps to lower speeds, without a corresponding change in contact length. It was decided that specimen tension should be investigated for its effects on abrasion resistance. The most logical way to do this was to abrade in the parallel configuration with the larger wheel driven by the smaller motor, using a 3:1 timing pulley reduction. This permitted testing at 80 fps using this larger wheel. Data generated in this testing was then compared to results obtained previously in testing with the smaller wheel and therefore approximately one half the specimen tension associated with testing on the larger wheel. Individual test results are given in Tables 11 and 12.

A. Kevlar on Kevlar (Nylon on Nylon) Parallel Abrasion

The Kevlar materials used in this testing were the 6,000 lb webbing, the 2,000 lb braid and the 3/4 inch 500 lb tape. The 6,000 nylon webbing and 2,000 lb nylon braid were also used in this testing. Figures 57 through 61 compare results of testing at 80 fps with high and low specimen tension using the same contact force for each test series.

1. The 1 Inch 6,000 Lb Kevlar Webbing

The 6,000 lb Kevlar webbing (Figure 51) showed the greatest effect of tension on strength loss as specimens abraded under low tension lost approximately 25% more strength than those abraded under high tension. Only mild scorching was evident in the specimen abraded for 60 seconds. The rate of abrasion was low initially and decreased to near zero at about 45 seconds. This was similar to what was seen in the testing at 160 fps (Figure 6) except at the higher speed, the rate of abrasion was much higher initially and decreased rapidly to near zero at about 5 seconds contact time. In this testing, however, severe scorching was evident in very short contact times. This data appeared consistent with testing performed at 160 fps. Indications from this testing were that the shape of the curve in Figure 6 is a result of abrasion on the larger diameter wheel and that if tests could have been performed at 160 fps using the smaller wheel, the strength losses would have been higher and the shape of the curve similar to the curves for testing at 120 and 80 fps with the smaller wheel.

Although this effect seemed real, the reasons for it were not completely understood. The high tension in the specimen tended to decrease warp crimp and smooth the pronounced knuckles on the fabric surface. It seemed logical that this would tend to decrease abrasion but the reason for a near zero rate of abrasion after some contact was not clear.

2. 2,000 Lb Kevlar Braid

The Kevlar braid did not exhibit as great an effect of tension on strength loss as the webbing did. However, Figure 58 shows that the initial rate of abrasion was higher for the high tension specimens than the low. Also,

TABLE 11

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR ON KEVLAR (NYLON ON NYLON) PARALLEL CONFIGURATION USING HIGHER SPECIMEN TENSION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds)											
				3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	15	80	6,090		2		0			16			23		20
2,000 lb Kevlar Braid	5	80	2,270		44		47			63			54		48
3/4 inch 500 lb Kevlar Webbing	5	80	605		12		17			27					36 30 42
1 inch 6,000 lb Nylon Webbing	5	80	6,740		1[1]		20 68			82 76			91 82		95
2,000 lb Nylon Braid	2.5	80	2,540		21	4 61[2]	93 95[3]	99	94	89		98	99[4]		

1. Control value 6,750 pounds.
2. Contact time 12 seconds.
3. Contact time 17 seconds.
4. Contact time 55 seconds.

TABLE 12

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL CONFIGURATION USING HIGHER SPECIMEN TENSION

Material	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	10	15	20	25	30	35	40	45	50	60
1 inch 6,000 lb Kevlar Webbing	5	80	6,090		55	77		91		96		99		100	
2,000 lb Kevlar Braid	5	80	2,270		53		52			55			63		62 67
1-3/4 inch 4,000 lb Kevlar Webbing	1	80	4,170		63		72			86			92		97
1 inch 6,000 lb Nylon Webbing	5	80	6,750		89		98			99			99		99
2 inch 1,000 lb Nylon Ribbon	1	80	1,150		60	71		84		97	100				

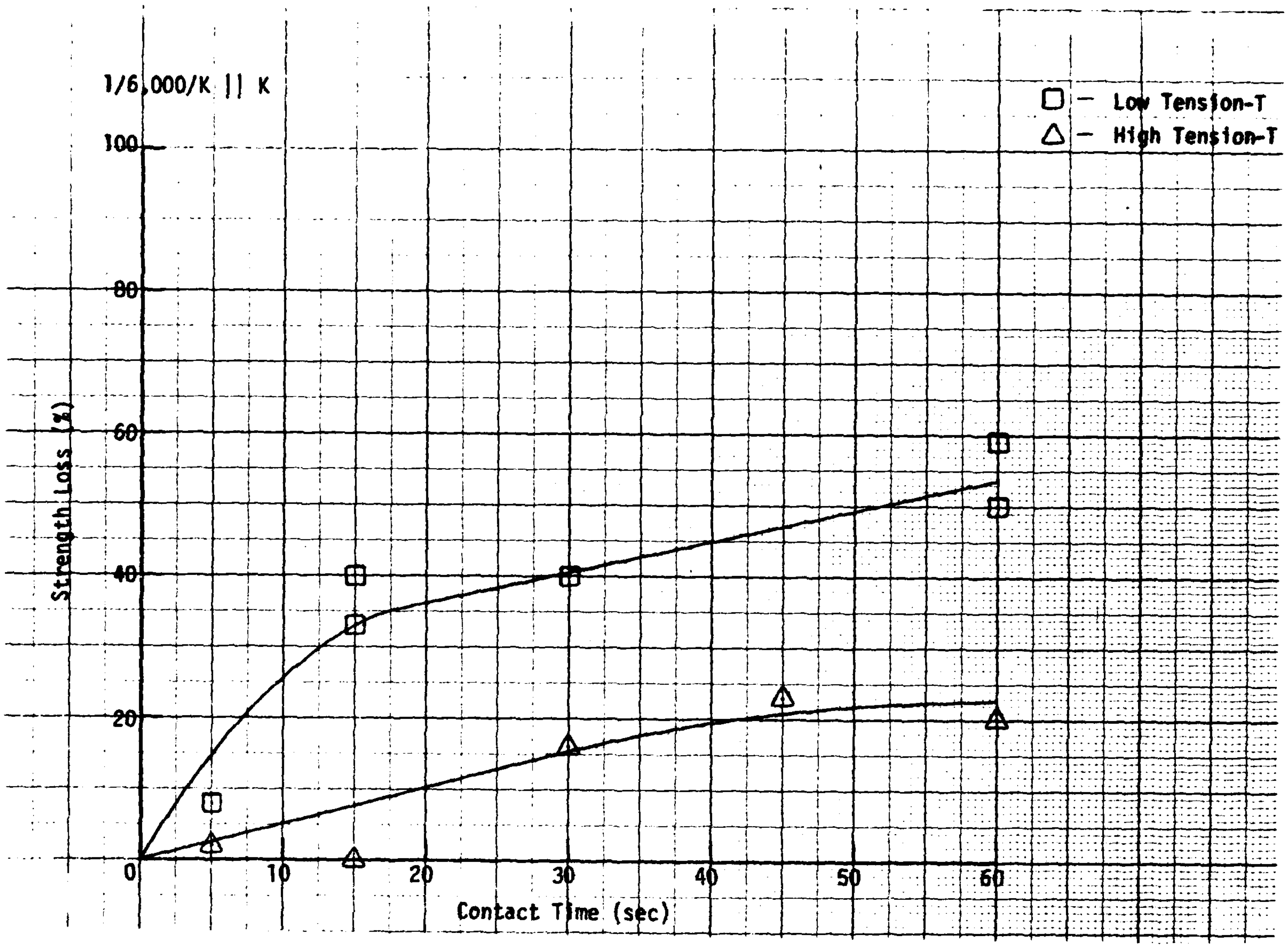


Figure 57. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 15 Lb and a Contact Speed of 80 fps

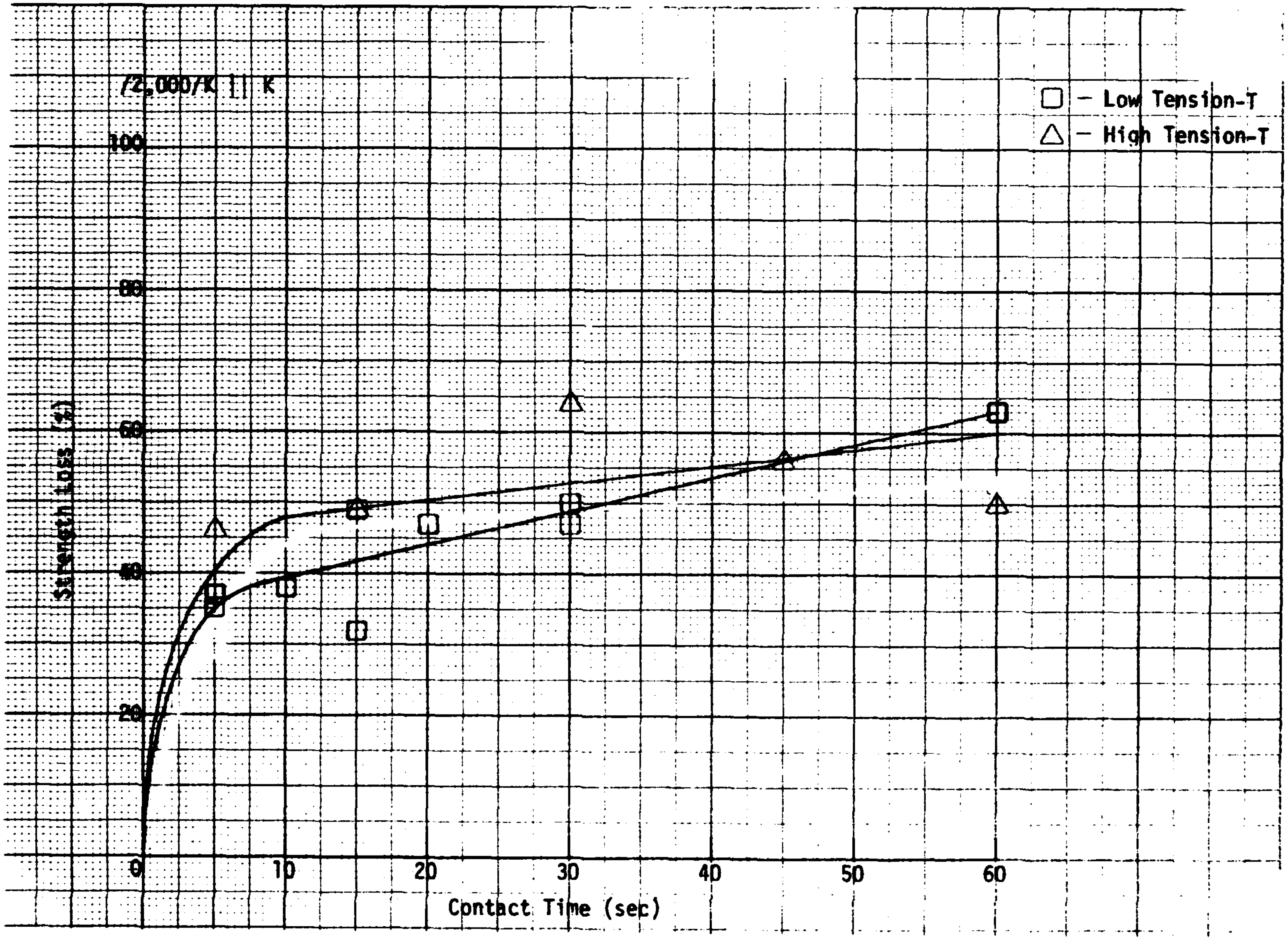


Figure 58. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 5 Lb and a Contact Speed of 80 fps

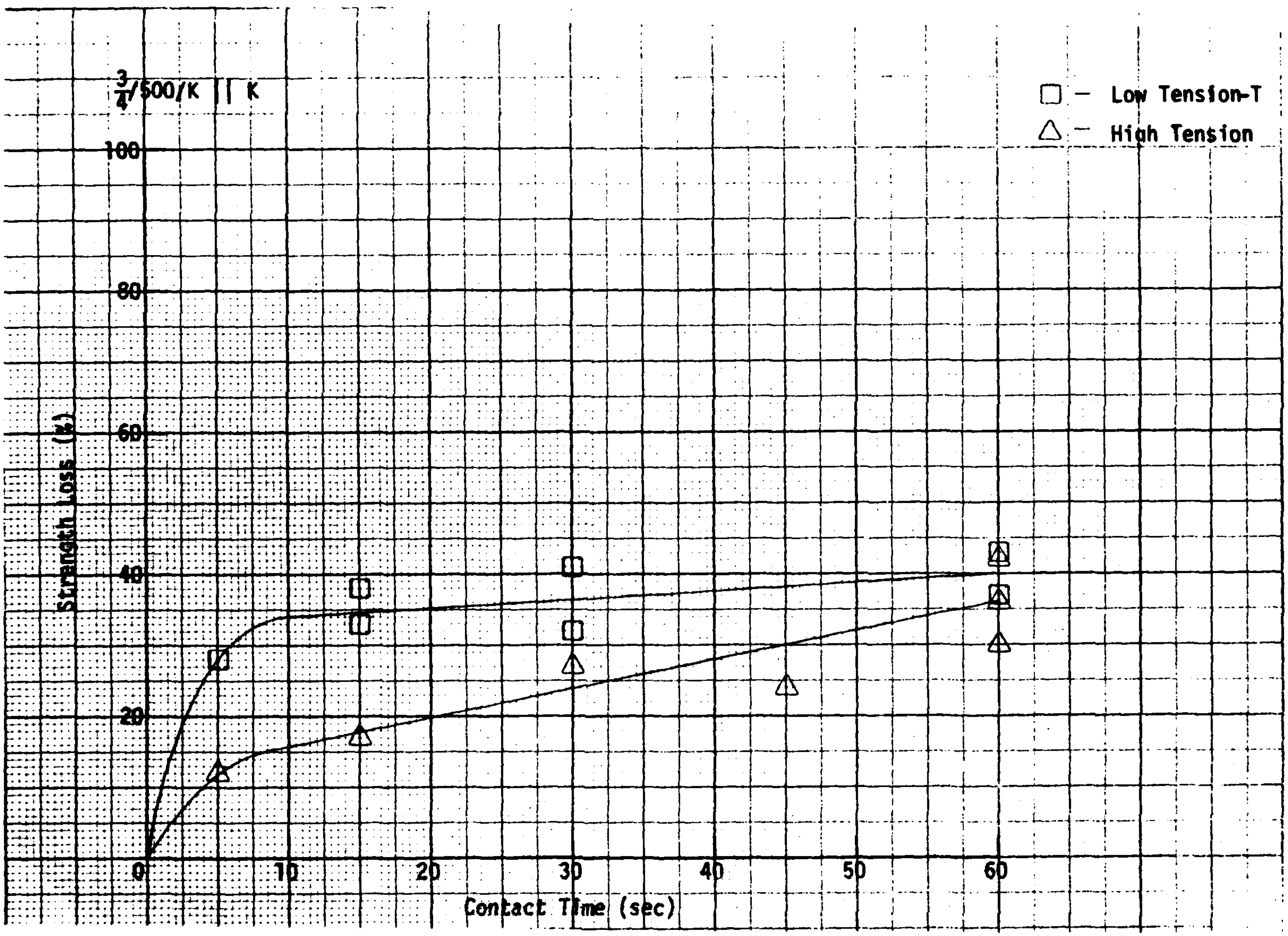


Figure 59. Strength Loss as a Function of Contact Time for a 3/4 Inch 500 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration Using a Contact Force of 5 Lb and a Contact Speed of 80 fps

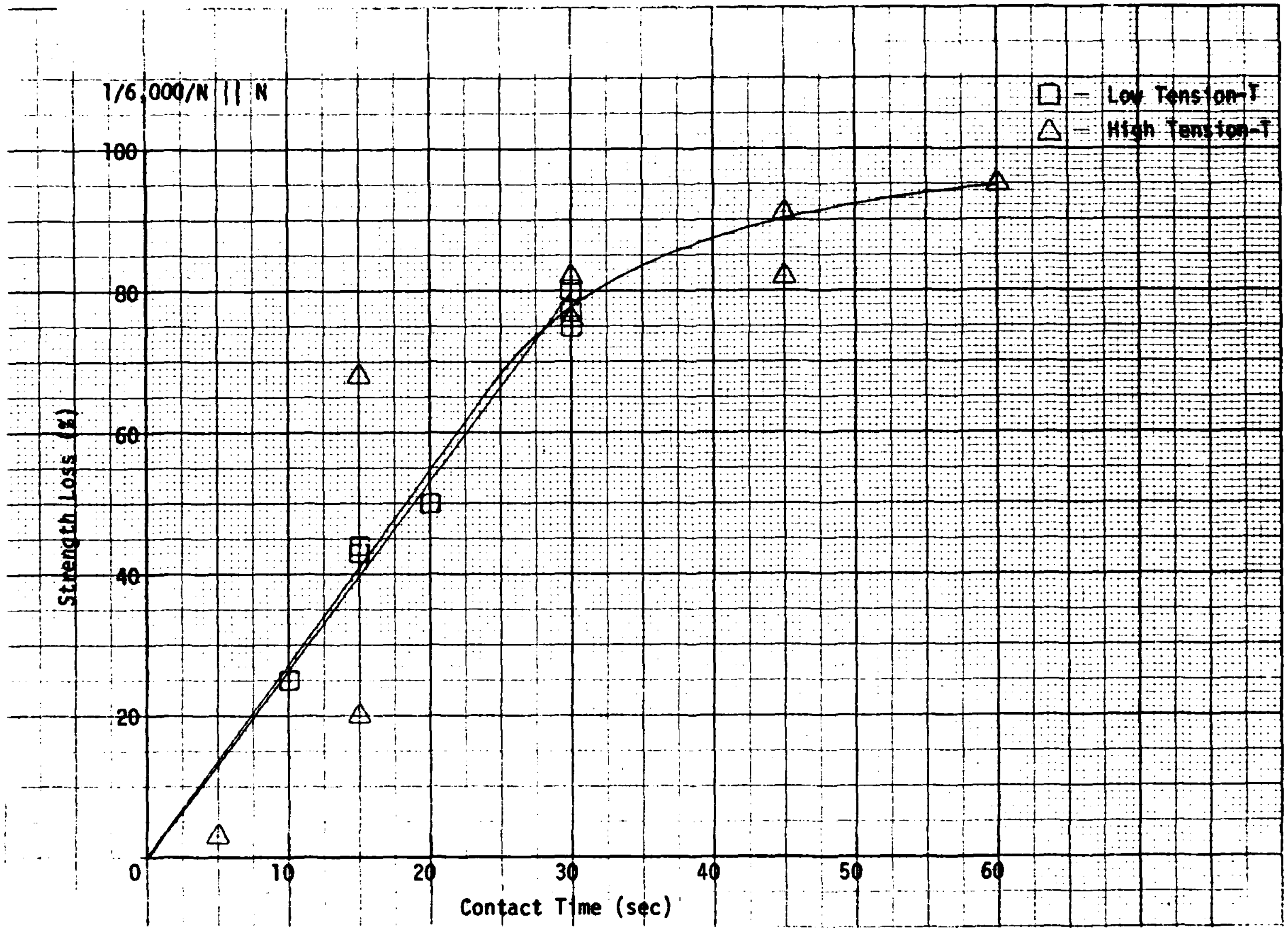


Figure 60. *Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Nylon Parallel Configuration Using a Contact Force of 5 Lb and a Contact Speed of 80 fps*

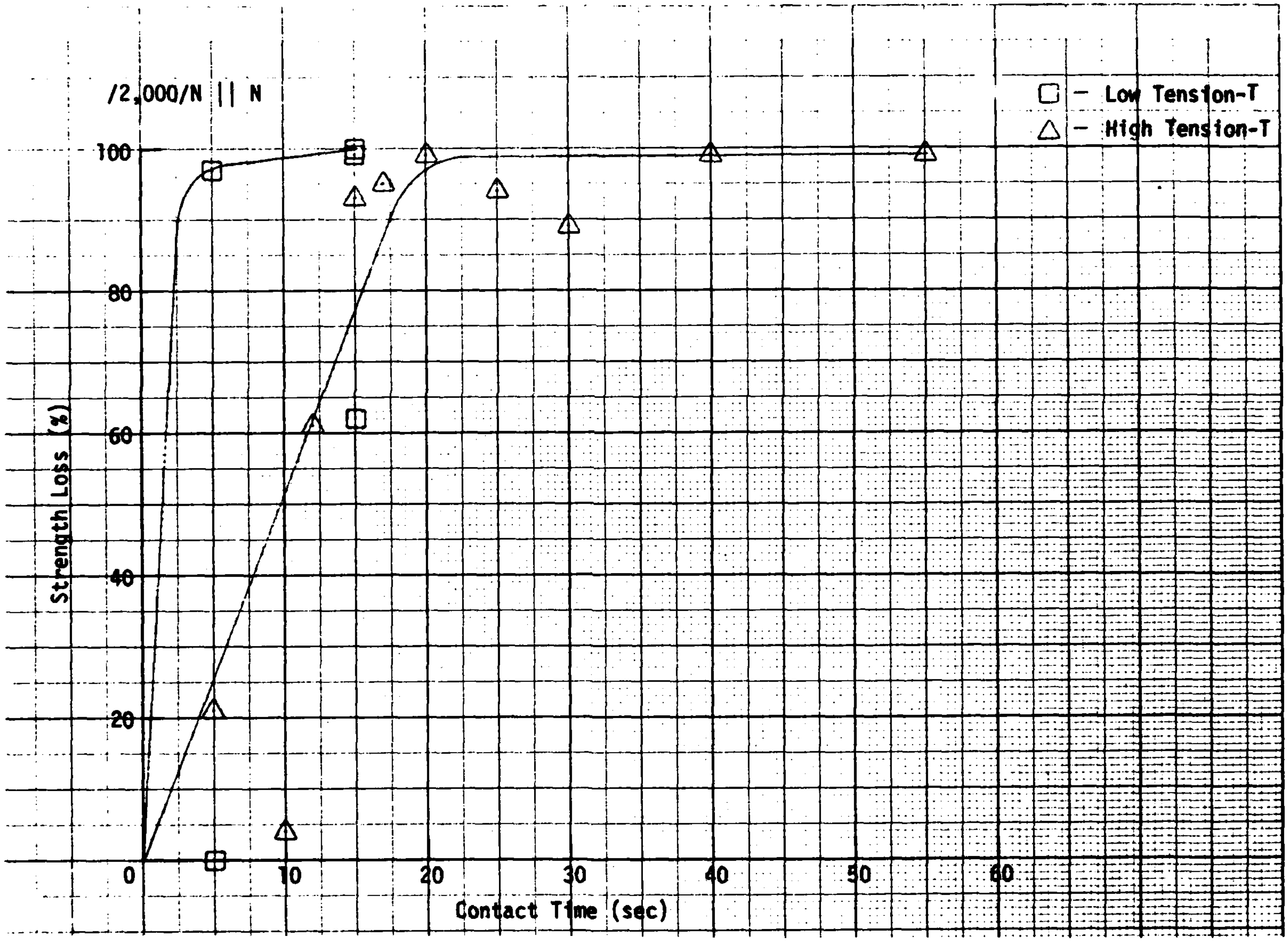


Figure 61. Strength Loss as a Function of Contact Time for a 2,000 Lb Nylon Braid Abraded in the Nylon on Nylon Configuration Using a Contact Force of 2.5 Lb and a Contact Speed of 80 fps

the rate of abrasion in the linear portion of the curve was lower for the high tension specimens than the low tension specimens. This resulted in an intersection of the two curves similar to what was seen in Figure 10 with the curves corresponding to testing at 120 and 160 fps. The curve corresponding to testing at 160 fps also had a high rate of abrasion initially and a rate of abrasion in the linear portion of the curve which was lower than that for the 120 fps curve. The two high tension curves (80 and 160 fps) also had very similar slopes in the linear region. This effect again appeared to be real and a reasonable explanation for the differences between curves corresponding to testing at 160 and 120 fps. The low rate of abrasion in the linear portion of the curves for high tension abrasion was explainable in terms of decreased surface roughness as the yarns were pulled inward toward the longitudinal axis of the structure with the increased tension. Also, as the tension increased, the orientation of the yarns within the structure changed, becoming more aligned with the longitudinal axis of the braid. This reduced the lateral shearing of the yarns. The high initial rate of abrasion only seemed explainable in terms of a lateral contraction of the braid essentially decreasing the contact area. This theory was reinforced by the severe scorching and glazing evident after short contact times in this testing.

3. 3/4 Inch 500 Lb Webbing

The testing of this material was different from testing of the webbing and braid in that it lacked any heat effects. Only very light scorching was seen at long contact times at 160 fps and at shorter contact times at 240 fps. No scorching was seen at 80 fps and never was there any glazing observed. Figure 59 compares results for low and high tension testing at 80 fps. The high tension in the plain weave again resulted in a low initial rate of abrasion due to the expected decrease in surface roughness and therefore coefficient of friction. The final transition to a lower, more uniform rate of abrasion occurred at approximately 5-10 seconds contact time as it did in all other testing (see Figure 7). However, the uniform rate of abrasion for the high tension testing was higher than that for the low tension testing but approximately equal to the uniform rate of abrasion found in testing at 160 fps. Close examination of Figure 7 revealed that abrasion at 80 and 120 fps (using the smaller wheel) never attained a uniform rate, but rather decreased with increasing contact time up until 60 seconds contact time. Whether this was an anomoly in the data or a true effect was not clear since the rate of decreasing rate of abrasion was decreasing very slowly and the data scatter (although low) allowed room for varying interpretations. However, these two curves had similar shapes as did the curves for high tension 80 fps and 160 fps testing. The odd shape of the curve for testing at 240 fps could have resulted from light scorching, first noticeable after 15 seconds contact time, and an accompanying decrease in the coefficient of friction. The convergence of the three high speed curves (Figure 7) and the 80 fps curves (Figure 59) at 60 seconds contact time was apparently a function of the test conditions. The data presented in Figure 59 definitely reinforces data gathered at speeds of 240 and 160 fps.

4. 1 Inch 6,000 Lb Nylon Webbing

Figure 60 presents results for low and high tension abrasion at 80 fps with the nylon webbing. In the original testing on the smaller wheel, strength loss was exclusively attributed to surface melting. As the abraded specimen melted, the molten nylon was deposited on the surface of the abrading

specimen and formed long curved spines protruding from it. These spines acted to wipe away molten nylon in successive passes. Figure 60 shows the similarities in performance of the webbing at low and high tension up to about 60% strength loss. The heat generation up to this point appeared to be similar for both test configurations. The length of the abrading specimen used on the larger wheel was two times the length used on the smaller wheel. With the larger wheel, a point on the abrading surface had twice the cooling time between successive contacts with the abraded specimen than with the smaller wheel. The initial heat buildup was similar for the two configurations because of the cool abrading surface at the start of the test. Once the abrading surface heated up, the rates of abrasion were different for the two configurations. Beyond 60% strength loss, the rate of abrasion decreased for the high tension specimen possibly because of the cooler abrasive surface. Perhaps a decrease in the coefficient of friction also allowed the abrading specimen to cool and reduced the melting. This, however, is pure conjecture since little is known about the temperatures in the abraded area during testing.

5. 2,000 Lb Nylon Braid

The results of testing the nylon braid at high and low tension, a test speed of 80 fps and 2.5 lb contact force are given in Figure 61. The results were similar to what was seen for the nylon webbing. The rate of abrasion was lower for the high tension specimen than the low tension specimen. This was most likely due to the lower heat generation affected by the length of the abrading sample since melting was the exclusive cause of strength loss. Both curves did have similar shapes.

B. Kevlar (Nylon) on Abrasive Surface Parallel Abrasion

1. 1 Inch 6,000 Lb Kevlar Webbing

Figure 62 compares results for abrasion of the 6,000 lb Kevlar webbing at high and low tension when abraded in this configuration at 80 fps using a 5 lb contact force. Table 12 presents individual test results. No scorching was evident in any specimens tested. The effect of tension in this testing was much less than in the Kevlar on Kevlar testing although the tensions used in this testing were also lower. The shapes of the curves in Figure 62 are very similar. Strength losses in the high tension specimens were slightly higher than the strength losses in the low tension specimen. Fiber tensile failure could have occurred with slightly less abrasion under high tension. The effect of fabric surface did not seem to be as great an effect in this testing as it appeared to be in the Kevlar on Kevlar testing. In any event, the effect of tension appeared to be minor in this testing.

2. 2,000 Lb Kevlar Braid

Figure 63 compares results for the 2,000 lb Kevlar braid abraded under high and low tension at 80 fps. The results were similar to what was seen in the Kevlar on Kevlar testing (Figure 58). Scorching was evident in all specimens tested. The initial rate of abrasion was high, most likely due to the lateral contraction of the braid under high tension. The rate of abrasion in the linear portion of the curve was lower for the high tension specimen up until convergence of the curves at approximately 30 seconds contact time. This was probably due to orientation of the yarns parallel to the longitudinal axis of the braid under high tension. However, the effect of tension was only significant at short contact times.

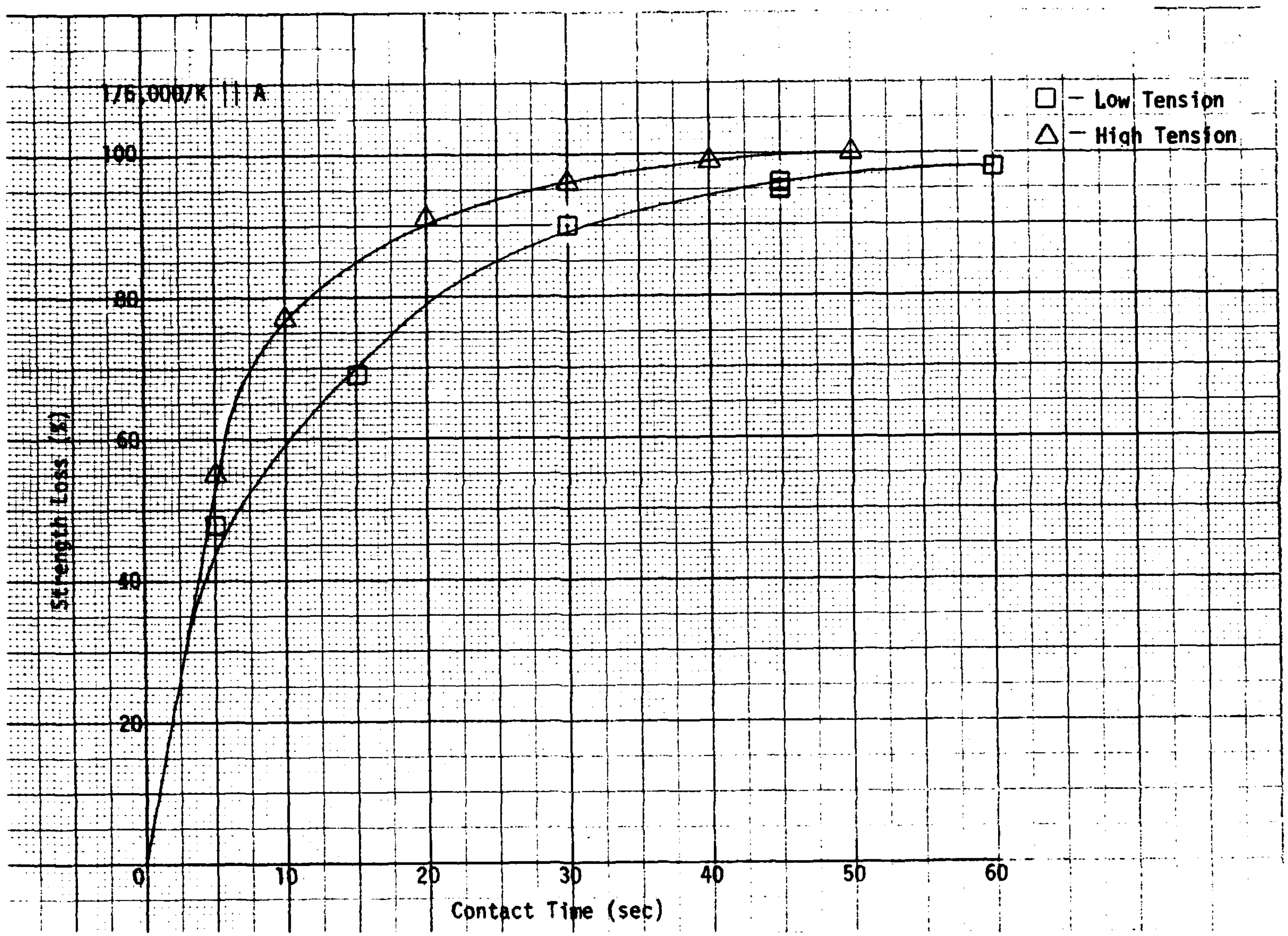


Figure 62. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 5 Lb and a Contact Speed of 80 fps

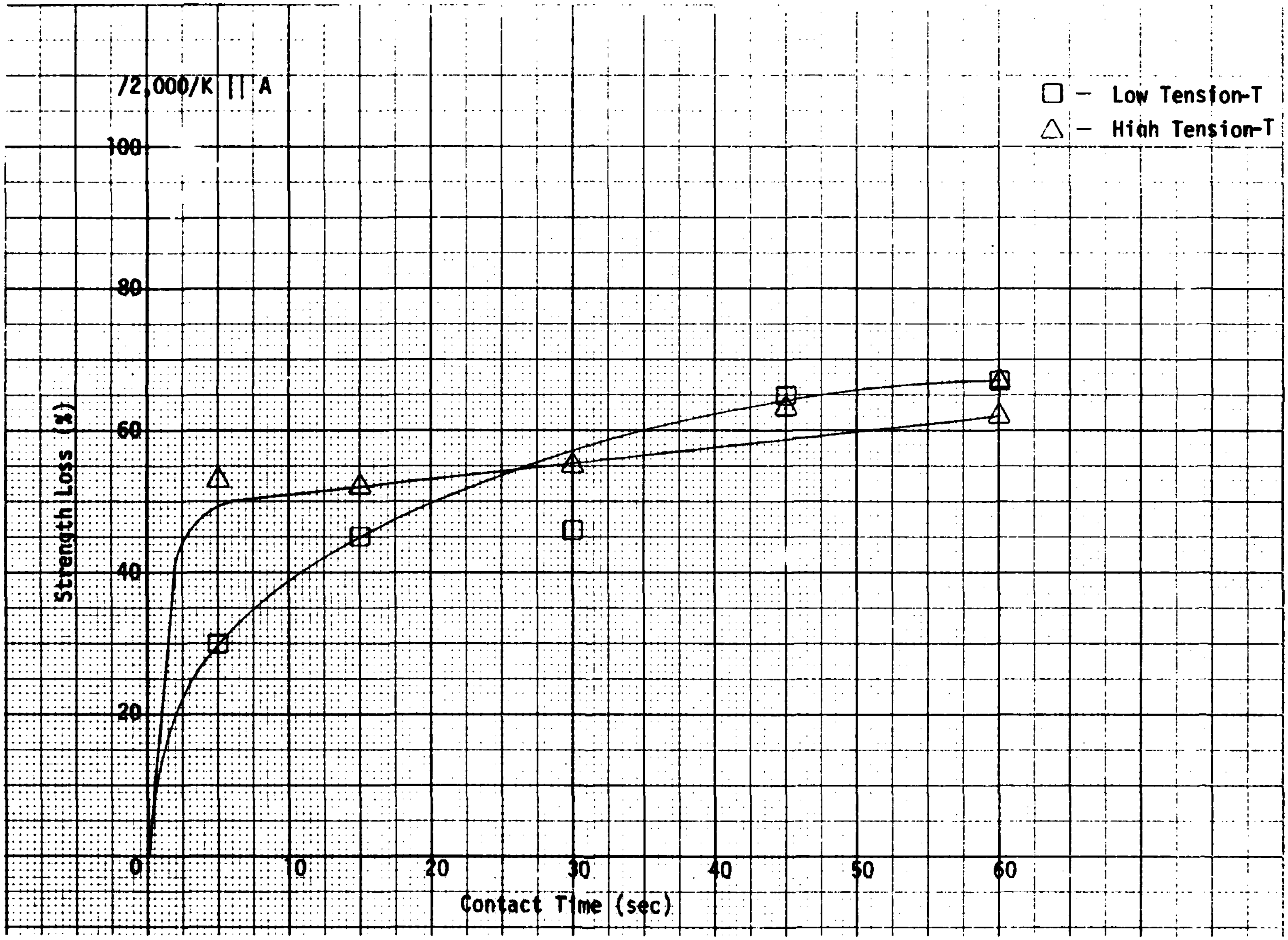


Figure 63. Strength Loss as a Function of Contact Time for a 2,000 Lb Kevlar Braid Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and a Contact Speed of 80 fps

3. 1-3/4 Inch 4,000 Lb Kevlar Webbing

Figure 64 shows the results of testing the 4,000 lb Kevlar webbing at high and low tension. The results were similar to what was seen with the 6,000 lb Kevlar webbing (Figure 62). No scorching was evident in any specimens tested. The shapes of the curves were similar in Figure 64. Strength losses were slightly higher for the high tension specimens. This could have been attributed to fiber tensile breaks with less abrasive damage at the higher tension. The effect, here again, appeared to be minor, although specimen tension and variation from low to high was small.

4. 1 Inch 6,000 Lb Nylon Webbing

Figure 65 presents the results of abrasion of the nylon webbing at high and low tension. Here again, strength losses were slightly higher for the high tension specimens. Severe melting was evident in all specimens tested. The curves in Figure 65 were similar in the initial portion. The high tension specimen sustained no further strength loss after 20 seconds contact time. This was probably due to a drastic reduction in the coefficient of friction by the molten nylon. Although this seemed to be the greatest difference between high and low tension abrasion, the strength of the specimen had essentially been completely lost at that point. The effect of tension was again found to be minor over the range of tensions investigated.

5. 2 Inch 1,000 Lb Nylon Ribbon

Figure 66 compares the results of ribbon testing at high and low tension. The effects of tension were greater in this testing than in any other testing in this configuration. No melting was evident in any of the specimens tested. Strength losses were higher for high tension specimens and the decrease in rate of abrasion seen in the low tension specimens was not evident in the high tension specimens. Specimens under high tension abraded completely through in 35 seconds where low tension specimens were run for 60 seconds with 90% strength loss. The reasons for this were not understood and considering the low tension used and the small difference between tensions, the effect seemed quite large. However, there was a substantial difference in performance seen between parallel (low tension) and perpendicular (high tension) abrasion, discussed in previous sections, which was thought to be at least partially attributable to the different tensions used.

C. Summary

This test series did not show any significant effect of specimen tension on abrasion resistance which was not attributable to changes in the geometry of the situation. Plain weave constructions such as the 6,000 lb and 500 lb Kevlar webbings tended to show improved abrasion resistance with increased tension especially during initial contact. This was attributed to the decrease in surface roughness with increasing tension. The Kevlar braid showed poorer abrasion resistance with increased tension especially at initial contact most likely due to its decreased diameter at high tension. However, this braid also exhibited a lower rate of abrasion damage at longer contact times which may have been due to a longitudinal yarn orientation of yarns at high tension.

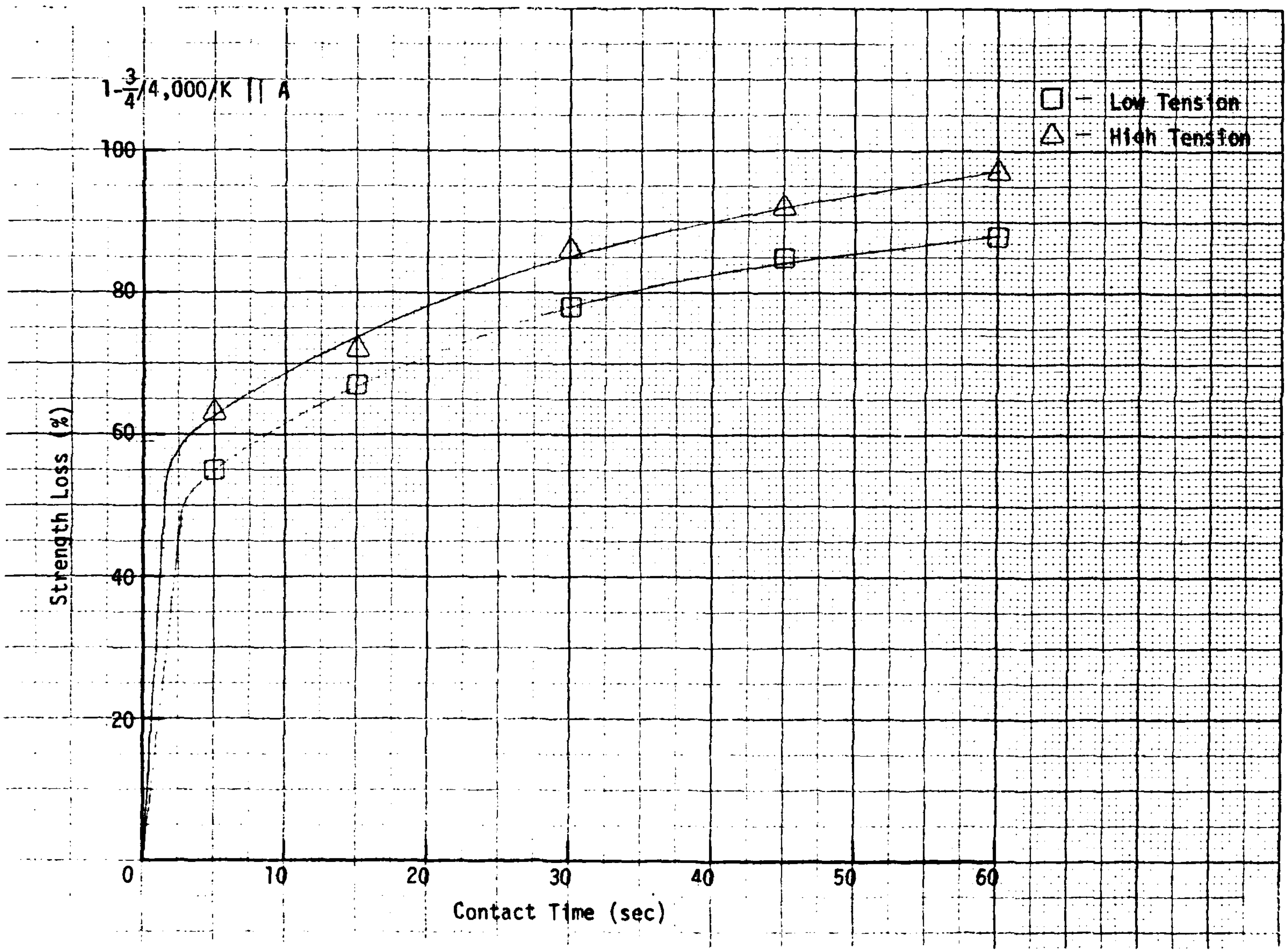


Figure 64. Strength Loss as a Function of Contact Time for a 1-3/4 Inch 4,000 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and a Contact Speed of 80 fps

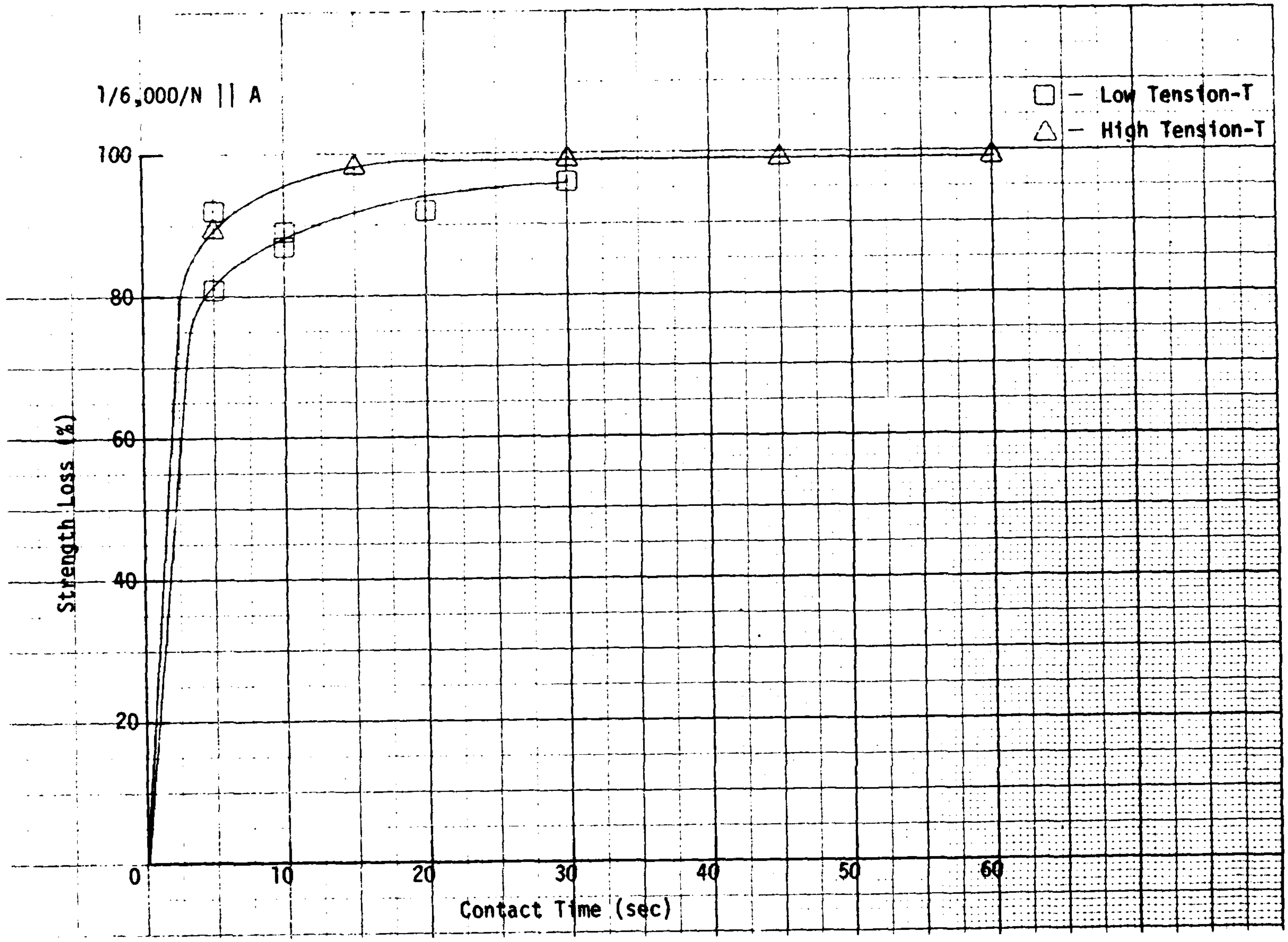


Figure 65. Strength Loss as a Function of Contact Time for a 1 Inch 6,000 Lb Nylon Webbing Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and a Contact Speed of 80 fps

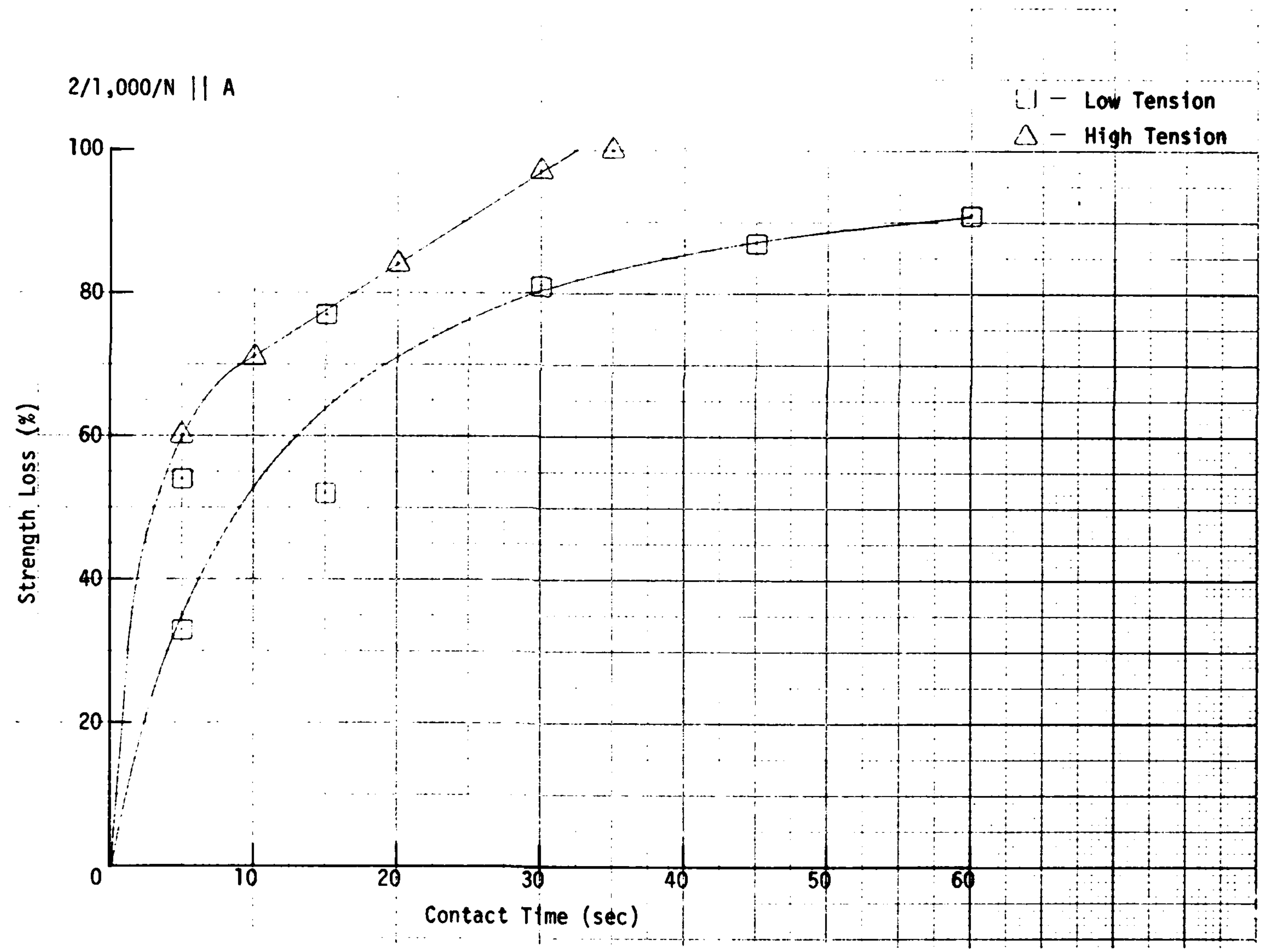


Figure 66. Strength Loss as a Function of Contact Time for a 2 Inch 1,000 Lb Nylon Ribbon Abraded in the Nylon on Abrasive Parallel Configuration Using a Contact Force of 1 Lb and a Contact Speed of 80 fps

Some nylon materials which exhibited melting as a form of strength loss also exhibited slightly better abrasion resistance at high tension which may have been due to a difference in heat generation between the large and small wheels. In all, conclusions from this testing were not clear and definite and direct effects of specimen tension on abrasion resistance were not obvious.

SECTION X

INVESTIGATION OF FIBER DAMAGE IN KEVLAR

In an attempt to investigate scorching, glazing and fiber breakage in abraded Kevlar specimens, some photographs of abraded specimens were taken at high magnification using a Scanning Electron Microscope (SEM). These photographs are presented in Figures 67 through 71.

A. Webbings

Figures 67 and 68 are photographs of scorched knuckles on the 1 inch 6,000 lb Kevlar webbing abraded in the Kevlar on Kevlar parallel and perpendicular configurations, respectively. Figure 67 shows scorched fiber ends at the leading edge of the knuckle. Most of the fiber ends exhibited very little splitting or fibrillation normally typical of tensile failures[3]. Almost all of these fibers were flattened at the tips during abrasion which indicated either melting and smearing or high transverse pressure and a possible softening and shearing of the fibers. Photographs C and D in Figure 67 were taken of fibers shown in the upper left corner of photograph B. These photographs show that there was some splitting and cracking of the fiber ends but the fibrils in general appeared to be bonded together. Photograph A in Figure 67 showed an apparent smear which was several fiber diameters in width. This appeared to be bonded to intact fibers of circular cross-section which indicated a migration of molten material.

Figure 68A shows a glazed and scorched warp yarn knuckle on a webbing which was abraded in the Kevlar on Kevlar perpendicular configuration. Photograph B of this figure shows the glazed area just to the left of center in photograph A. This appeared to be a smearing of molten material. The fibers barely visible in the backgound appeared to be relatively untouched during abrasion. Photograph C shows the clump of protruding fibers located just above the glazed area in photograph A. These fibers exhibited fibrillation which indicated a tensile or shearing mode of failure. They appeared to have been pushed into a small crevice between the knuckles after failure, which protected most of them from further damage. Some of the fibers near the surface did exhibit some flattening, probably from rubbing after initial failure. Photograph D in Figure 68 shows the protruding group of fibers located to the right of the glazed area in photograph A. Most of the fibers in this group were once connected with the fibers in photograph C. These fibers were polished during abrasion as they were pushed toward the yarn and held on the surface by the action of the abrading specimen. These fibers were also flattened without fibrillation at the tips due to the shearing action indicating a possibility of softening or melting.

B. Braids

Figure 69 shows photographs taken with an SEM of the glazing of Kevlar braids abraded in the Kevlar on Kevlar perpendicular configuration. Photographs a and b were taken of a braid abraded at a speed of 20 fps for 7 seconds using a contact force of 10 lb. This braid showed a glazing without scorching upon inspection after testing. Photograph A shows fibers deflected due to transverse rubbing and bonded or smeared due to an apparent melting of the

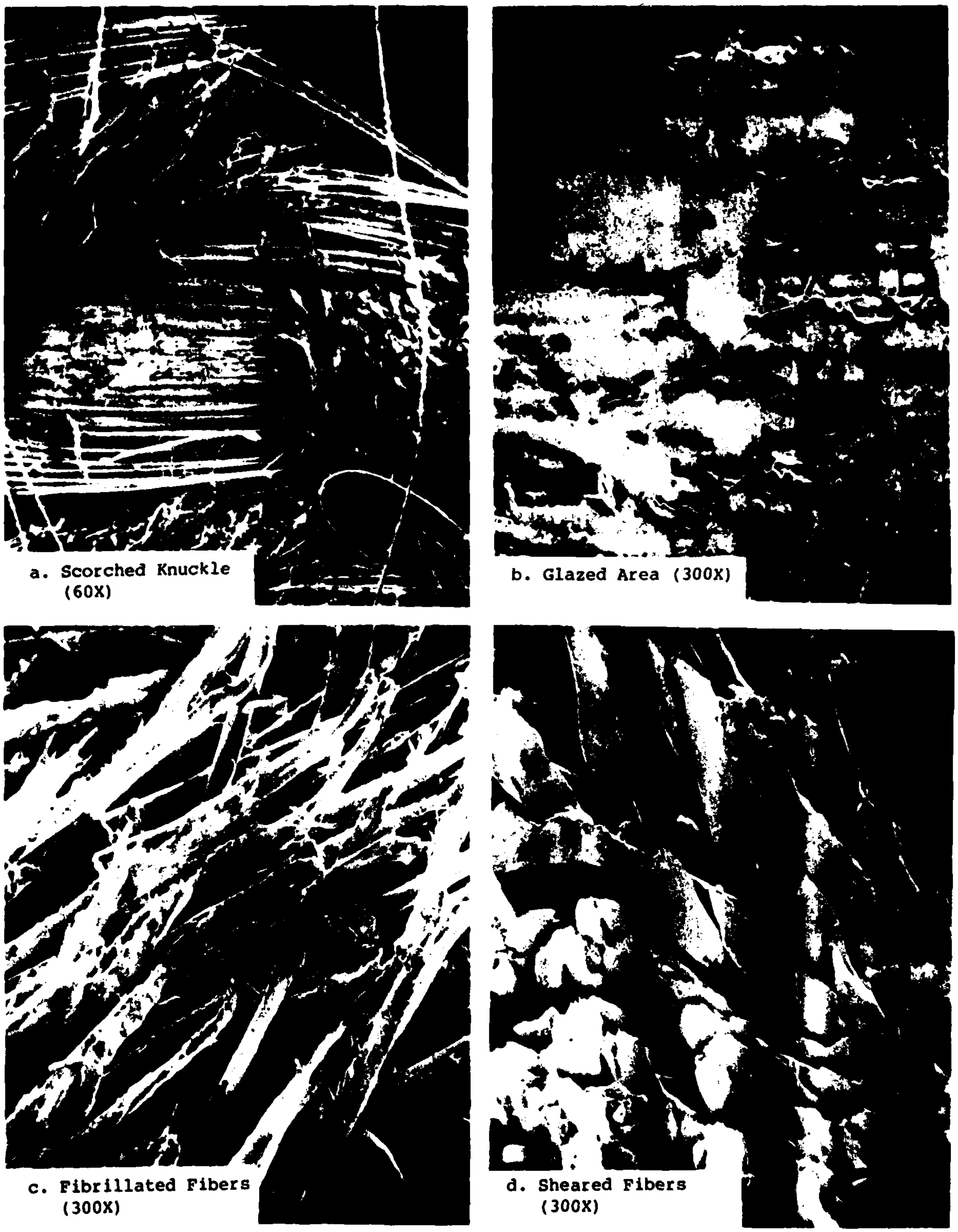
a. Scorched Fibers (100X)

b. Scorched Fibers (100X)

c. Scorched Fibers (300X)

d. Scorched Fibers (1000X)

Figure 67. Photographs of Scorched Fibers on a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Parallel Configuration at a Speed of 160 fps Using a Contact Force of 15 Lb and a Contact Time of 30 Seconds



a. Scorched Knuckle (60X)

b. Glazed Area (300X)

c. Fibrillated Fibers (300X)

d. Sheared Fibers (300X)

Figure 68. Photographs of Scorched Knuckle and Fibers on a 1 Inch 6,000 Lb Kevlar Webbing Abraded in the Kevlar on Kevlar Perpendicular Configuration at a Speed of 240 fps Using a Contact Force of 5 Lb

a. Apparent Melting and Bonding of Fibers (100X)

b. Apparent Melt Migration and Adhesion to Unabraded Fibers (300X)

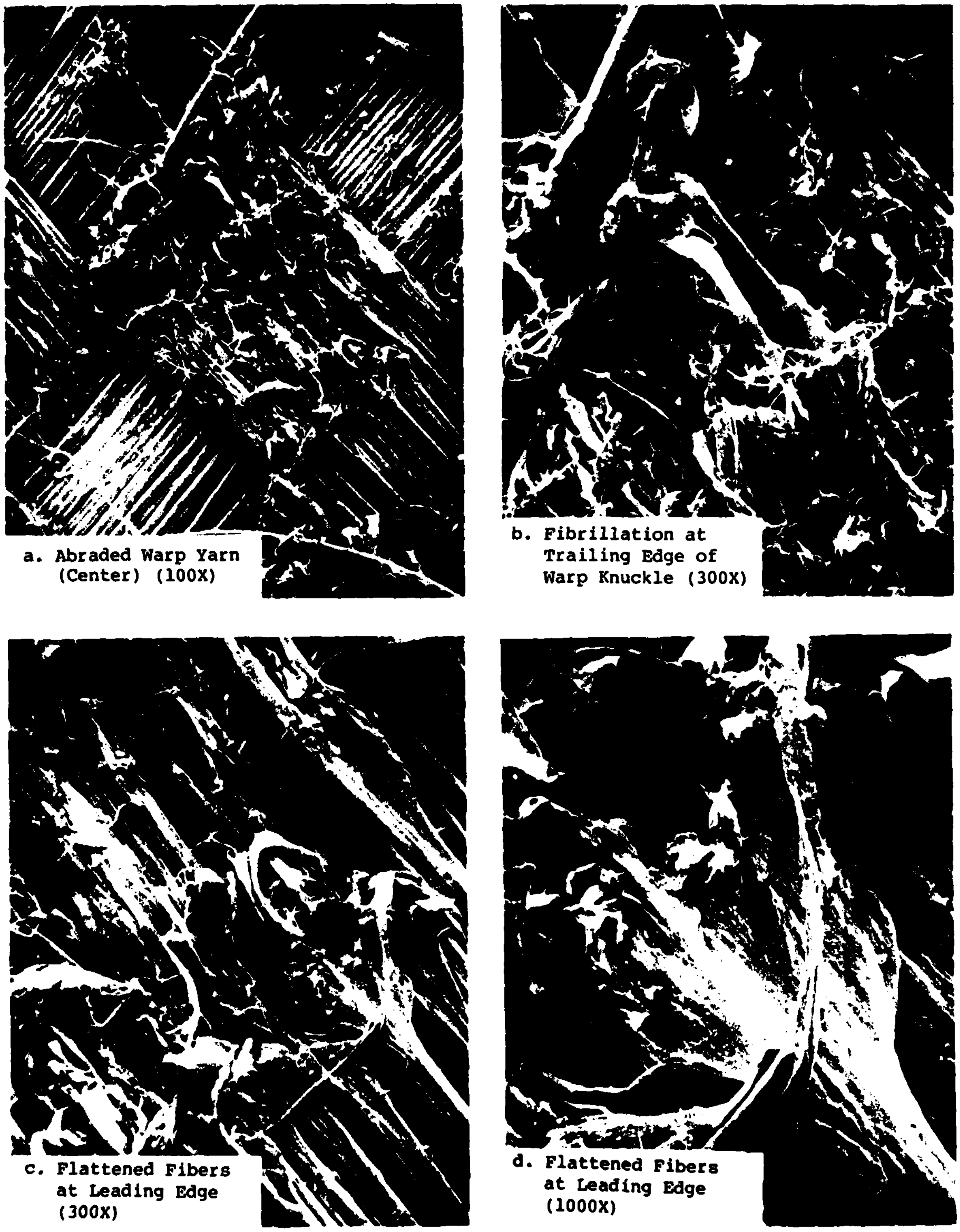
Test Conditions: Speed - 20 fps; Contact Force - 10 lb; Contact Time - 7 sec

c. Bonded Fibers (300X)

d. Bonded Fibers (300X)

Test Conditions: Speed - 40 fps; Contact Force - 5 lb; Contact Time - 10 sec

Figure 69. Photographs of Glazed Area of Kevlar Braids Abraded in the Kevlar on Kevlar Perpendicular Configuration at Two Different Test Conditions



a. Abraded Warp Yarn (Center) (100X)

b. Fibrillation at Trailing Edge of Warp Knuckle (300X)

c. Flattened Fibers at Leading Edge (300X)

d. Flattened Fibers at Leading Edge (1000X)

Figure 70. Photographs of an Unscorched 2 Inch 1,000 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 40 fps for 10 Seconds Using a Contact Force of 1 Lb

a. Abraded Warp → and Fill ↑ Yarns (100X)

b. Abraded Warp → and Fill ↑ Yarns (200X)

c. Abraded Fill Yarn (600X)

d. Abraded Fill Yarn (2000X)

Figure 71. Photographs of an Unscorched 2 Inch 1,000 Lb Kevlar Ribbon Abraded in the Kevlar on Abrasive Perpendicular Configuration at a Speed of 80 fps for 3 Seconds Using a Contact Force of 1 Lb

fibers. Photograph B shows thin sheets of Kevlar wrapped around apparently unabraded fibers which indicated a migration of the molten Kevlar. Photographs C and D were taken of a braid abraded at a speed of 40 fps for 10 seconds using a contact force of 5 lb. Photograph C shows a group of fibers which were sheared due to the transverse rubbing. There was some evidence of melting and bonding of these fibers at the tips. Photograph D shows a crack in a glazed area exposing the fibers. The cross-sections of these fibers appeared distorted as the tips were melted and bonded to form the glaze.

C. Ribbons

Figure 70 shows photographs of a 2 inch 1,000 lb Kevlar ribbon abraded in the Kevlar on abrasive parallel configuration at a speed of 40 fps for 10 seconds using a contact force of 1 lb. No scorching was evident in this specimen. Shown in the center of photograph A is an abraded warp yarn. The fill yarn shown on either side of the warp yarn was obviously unabraded. Photograph B shows the fibrillated fibers at the trailing edge of the warp knuckle. Photographs C and D show the fibers in the leading edge of the warp knuckle. These fibers were obviously flattened and smeared at the tips due to abrasion. The lack of severe cracking and fibrillation of the tips of these fibers indicated a possible melting or softening due to the high speed rubbing.

Figure 71 shows photographs of a 2 inch 1,000 lb Kevlar ribbon abraded in the Kevlar on abrasive perpendicular configuration. No scorching was evident in this specimen. Photographs A and B show obvious abrasion of both warp and filling. Abrasion of the filling yarn was most likely due to the high specimen tension used in this testing and not in the parallel testing. Fibrillation was evident in both warp and fill yarns. Some warp yarns which were not severed did exhibit some smearing and flattening. Photographs C and D show flattening and smearing of fill yarns. This indicated a softening or melting of the fill yarns during abrasion.

D. Summary

Indications from these photographs were that some melting of Kevlar was occurring during abrasion, even where scorching was not evident. Bonding, smearing, and flattening of fibers with only minor cracking and fibrillation indicated a flow of material. Flow was also indicated by the deposits of material found on apparently unabraded fibers. In most cases, however, fibrillation was also present in these photographs. Indications were that initial fiber failure was not due to melting in these cases. Melting and smearing seemed to be occurring on the ruptured fiber ends which were still in contact with the abrading specimen after fiber failure.

SECTION XI

ABRASION OF IDENTICAL STRUCTURES MADE FROM KEVLAR AND NYLON

A comparison of abrasion resistance of Kevlar and nylon materials having the same rated strength was perhaps correct from the point of view of the decelerator system designer. However, because of substantial differences in the mechanical properties of Kevlar and nylon, fabric design to meet certain structural properties is also very different between the two materials. Previous testing showed that abrasion resistance was dependent upon fabric construction. Therefore, in order to get a true comparison of abrasion resistance between the two materials, constructional differences had to be minimized. For the purpose of comparison, three of the nylon materials were selected to be duplicated using Kevlar yarn and two Kevlar materials were selected to be duplicated using nylon yarn. In order to duplicate the geometry of the selected structure, the warp and filling yarns of the duplicates were plied and twisted to the exact specifications of the originals and the picks and ends per inch were also duplicated exactly in the weaving and braiding processes. However, the nylon and Kevlar yarns were not available in the same deniers. For this reason, 200 denier Kevlar yarn was used in place of nylon 210 denier, 1,000 denier Kevlar yarn was used in place of 840 denier nylon yarn and 1,260 denier nylon yarn was used in place of 1,500 denier Kevlar yarn. These choices were based on availability, but also they result in yarns having approximately equivalent diameters. Because of the difference in specific gravity and tenacity between nylon and Kevlar, the Kevlar structures were slightly heavier and much stronger than their nylon counterparts. Fabric width and surface characteristics were very similar between the originals and duplicates, however.

The nylon materials selected to be duplicated were the 1 inch 6,000 lb webbing, the 2 inch 1,000 lb ribbon and the 2 inch 460 lb ribbon. The Kevlar materials selected to be duplicated were the 1 inch 6,000 lb webbing and the 2,000 lb braid. All of the materials were tested on the abrasive surface at relatively low speeds where nylon's abrasion resistance compared most favorably with that of Kevlar. The 2 inch 800 lb Kevlar ribbon, which duplicated the 2 inch 460 lb nylon ribbon, was tested in the perpendicular configuration on the abrasive surface because of the excellent abrasion resistance of the nylon ribbon in this configuration. All of the other materials were tested in the parallel on abrasive surface configuration. Individual test results are given in Table 13.

A. Webbings

A 1 inch Kevlar webbing was woven according to the specifications for the 1 inch 6,000 lb nylon webbing which is a herringbone twill construction. This webbing had a strength of approximately 14,000 lb. The 1 inch 14,000 lb webbing was abraded in the Kevlar on abrasive surface parallel configuration at speeds of 40, 80 and 120 fps using a contact force of 5 lb. Abrasive damage appeared very uniform, no scorching was evident and tensile failures were good in this testing. The results of this testing were compared with the results of the testing of the 1 inch 6,000 lb nylon webbing in Figures 72 through 74. These figures show the obviously superior performance of the Kevlar webbing

TABLE 13

STRENGTH LOSS (%) DUE TO HIGH SPEED ABRASION OF KEVLAR AND NYLON WOVEN NARROW FABRICS AND BRAIDS ABRADED IN THE KEVLAR (NYLON) ON ABRASIVE SURFACE PARALLEL AND PERPENDICULAR CONFIGURATIONS

Material and Configuration	Contact Force (pound)	Contact Speed (fps)	Control Value (pound)	Contact Time (seconds) 3	5	7	10	12	15	20	25	30	35	45	60
1 inch 14,000 lb Kevlar webbing	5	40	14,600		25				31			48		35	42
parallel on	5	80	14,600		34				40			57		63	68
concrete					28				43			49		65	72
	5	120	14,600		35				50			71		76	82
1 inch 2,500 lb nylon webbing	5	20	2,890		45				58			66		76	85
parallel on concrete	5	40	2,890		76		87		92	100[1]					
2 inch 2,000 lb Kevlar ribbon	1	20	2,410		51[2]				45[2]			46		62	65
												52		56	63
parallel on concrete	1	120	2,410		76				85			89		88	93
1,000 lb nylon braid parallel on concrete	5	20	1,040	59	70	83	95	99[3]							
2 inch 700 lb Kevlar ribbon	1	20	705		26				40			46		55	53
perpendicular on concrete	1	40	705		31[4]		61[4]			55		60		93	
	1	80	810		63	66[5]	65		82 100[6]						

1. Contact time 22 seconds.
2. Control value 2,400 pounds.
3. Contact time 13 seconds.
4. Control value 810 pounds.
5. Contact time 8 seconds.
6. Contact time 17 seconds.

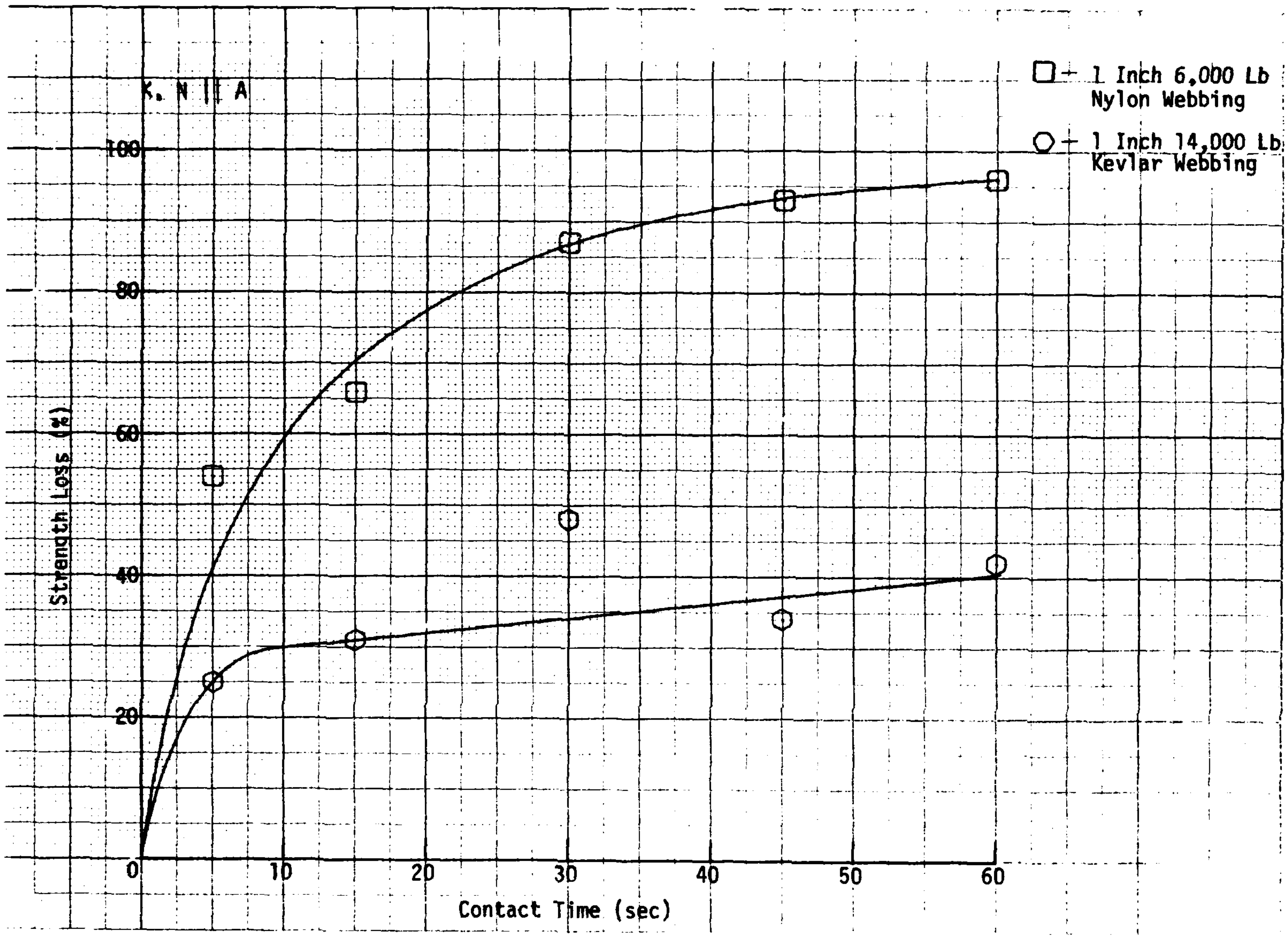


Figure 72. Strength Loss as a Function of Contact Time for Two Similar Webbings Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 40 fps Using a Contact Force of 5 Lb

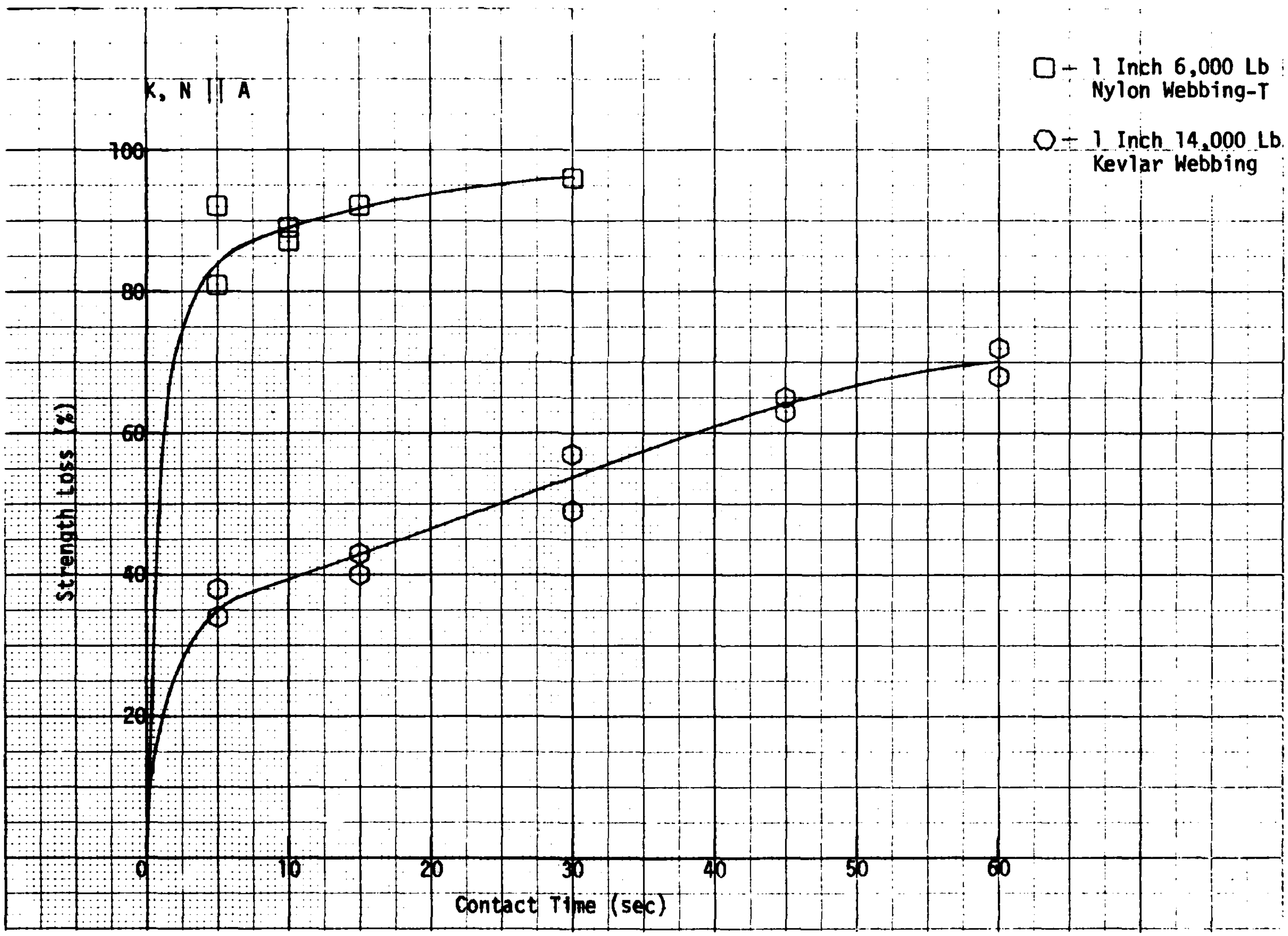


Figure 73. Strength Loss as a Function of Contact Time for Two Similar Webbings Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 80 fps Using a Contact Force of 5 Lb

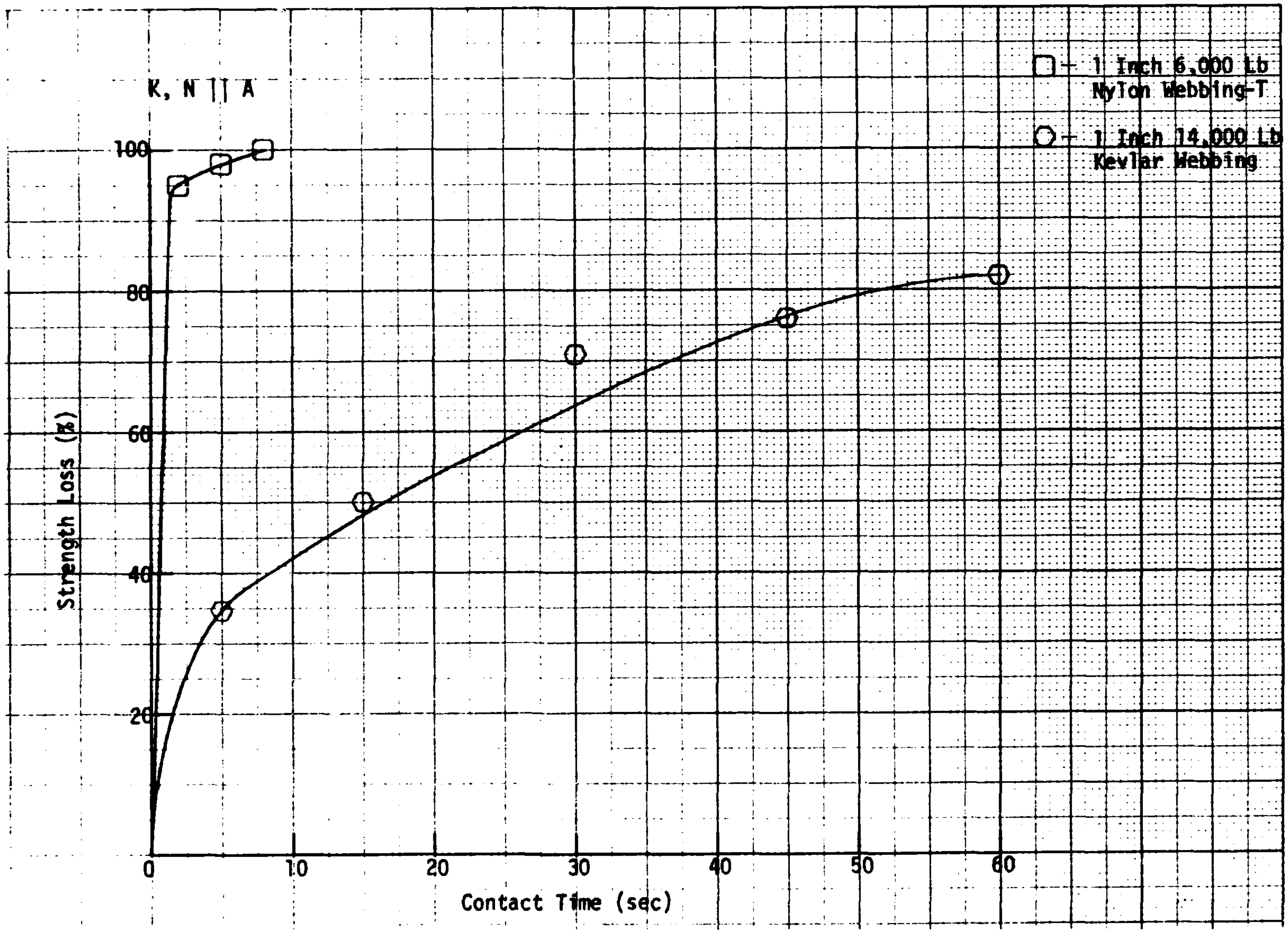


Figure 74. Strength Loss as a Function of Contact Time for Two Similar Webbings Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 120 fps Using a Contact Force of 5 Lb

over the nylon. Furthermore, the abrasion resistance of the nylon webbing decreased rapidly with increasing test speed while that of the Kevlar webbing was much less sensitive to speed.

In order to get a second comparison, and investigate the abrasion resistance of a plain weave nylon webbing, a 1 inch nylon webbing was woven to the specifications of the 1 inch 6,000 lb Kevlar webbing. This webbing had a strength of approximately 2500 lb. The 1 inch 2500 lb nylon webbing was abraded in the nylon on abrasive parallel configuration at speeds of 20 and 40 fps using a contact force of 5 lb. Abrasion was uniform in this testing and only slight melting was evident in samples abraded beyond 15 seconds at 40 fps. Tensile failures were generally good except where melting was evident. Figures 75 and 76 compare the results for the two similar webbings. The results were similar to what was seen with the twill webbings previously. The Kevlar webbing displayed abrasion resistance which was superior to that of nylon at both speeds. The abrasion resistance of the nylon webbing was also more speed dependent than the abrasion resistance of the Kevlar webbing. This effect was also seen with the previously tested webbings and was most likely due to the effect of heat on the properties of the fibers. This testing proved conclusively that Kevlar webbings exhibit abrasion resistance which is superior to that of nylon webbings when abraded at both high and relatively low speeds on a common surface. This conclusion had been assumed previously, based on initial test data generated previously. However, differences in fabric construction made this conclusion somewhat dubious at that time.

B. Braids

A nylon braid was fabricated to the exact specifications of the 2,000 lb Kevlar braid. The nylon braid had a tensile strength of 1,000 lb. The braid was abraded at a speed of 20 fps in the Kevlar on abrasive parallel configuration. Figure 77 compares the results of this testing with the results of testing the 2,000 lb Kevlar braid under the same conditions. The nylon braid exhibited melting in all specimens tested at this speed. The difference in abrasion resistance of the two materials was substantial. The Kevlar braid sustained only mild strength losses at this speed. The initial comparisons between the two 2,000 lb braids (Figures 34 and 35) showed that the Kevlar braid did exhibit abrasion resistance which was superior to that of the much larger nylon braid. The conclusion at that point was that the Kevlar braid was superior even in the face of adverse constructional differences. This test series supported that conclusion.

C. Ribbons

Two Kevlar ribbons were woven to the exact specifications of the 2 inch 1,000 lb and 460 lb nylon ribbons. These had tensile strengths of 2,000 lb and 700 lb respectively. The 2,000 lb ribbon was abraded in the Kevlar on abrasive parallel configuration at speeds of 120 fps and 20 fps using a contact force of 1 lb. No scorching was evident in any of the specimens tested. Previous testing of ribbons in this abrasion configuration showed that the abrasion resistance of the 1,000 lb nylon ribbon was better than all other ribbons tested. Figures 78 and 79 compare the results of testing both the 1,000 lb nylon ribbon and the 2,000 lb Kevlar ribbon under these conditions. At 20 fps (Figure 78) the abrasion resistance of the nylon ribbon was slightly superior to that of the 2,000 lb Kevlar ribbon which was similar to the abrasion resistance of the 4,000 lb Kevlar webbing. At 120 fps (Figure 79), both

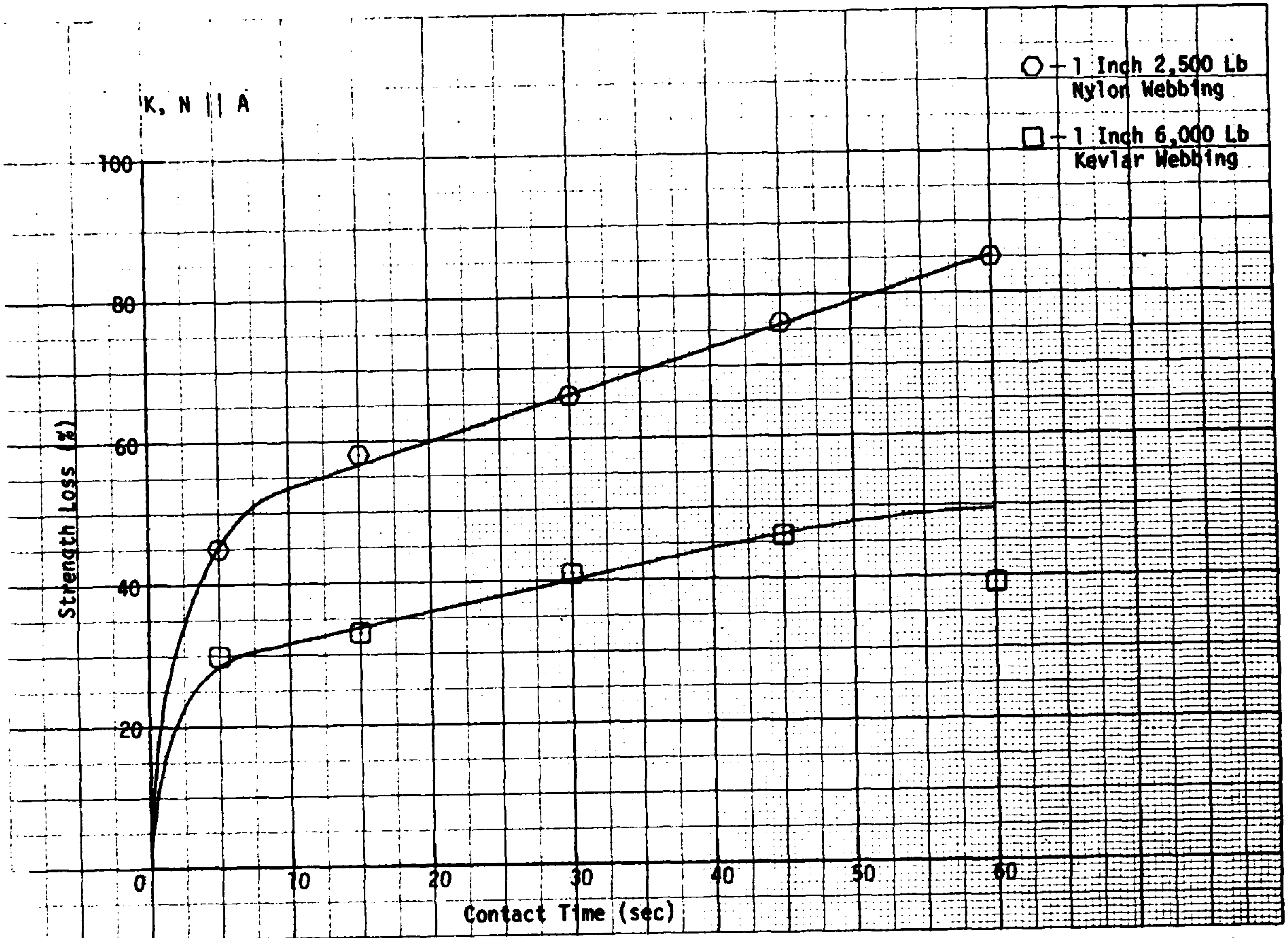


Figure 75. Strength Loss as a Function of Contact Time for Two Similar Webbings Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 20 fps Using a Contact Force of 5 Lb

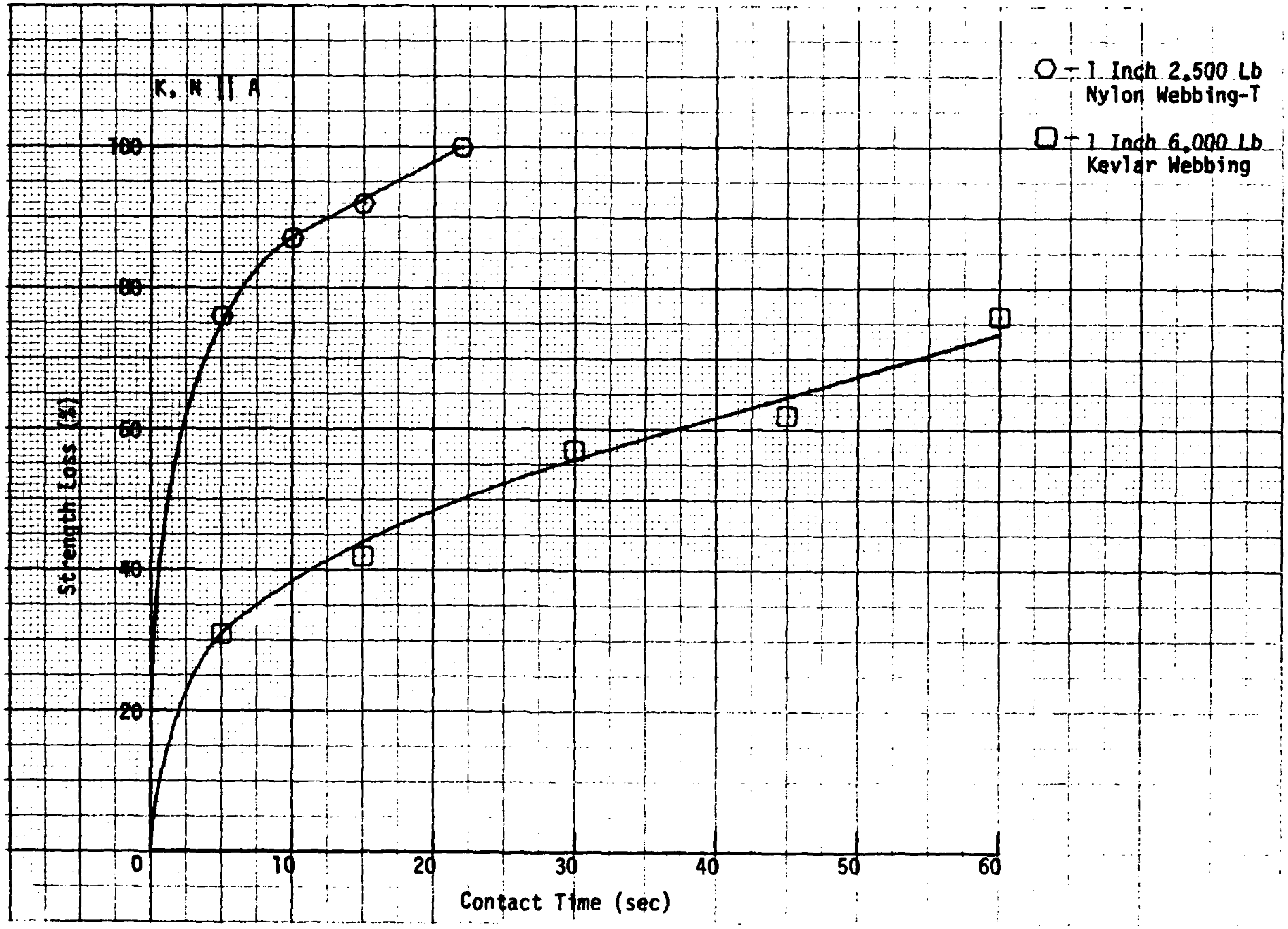


Figure 76. Strength Loss as a Function of Contact Time for Two Similar Webbings Abraded in the Kevlar on Abrasive Parallel Configuration at a Speed of 40 fps Using a Contact Force of 5 Lb

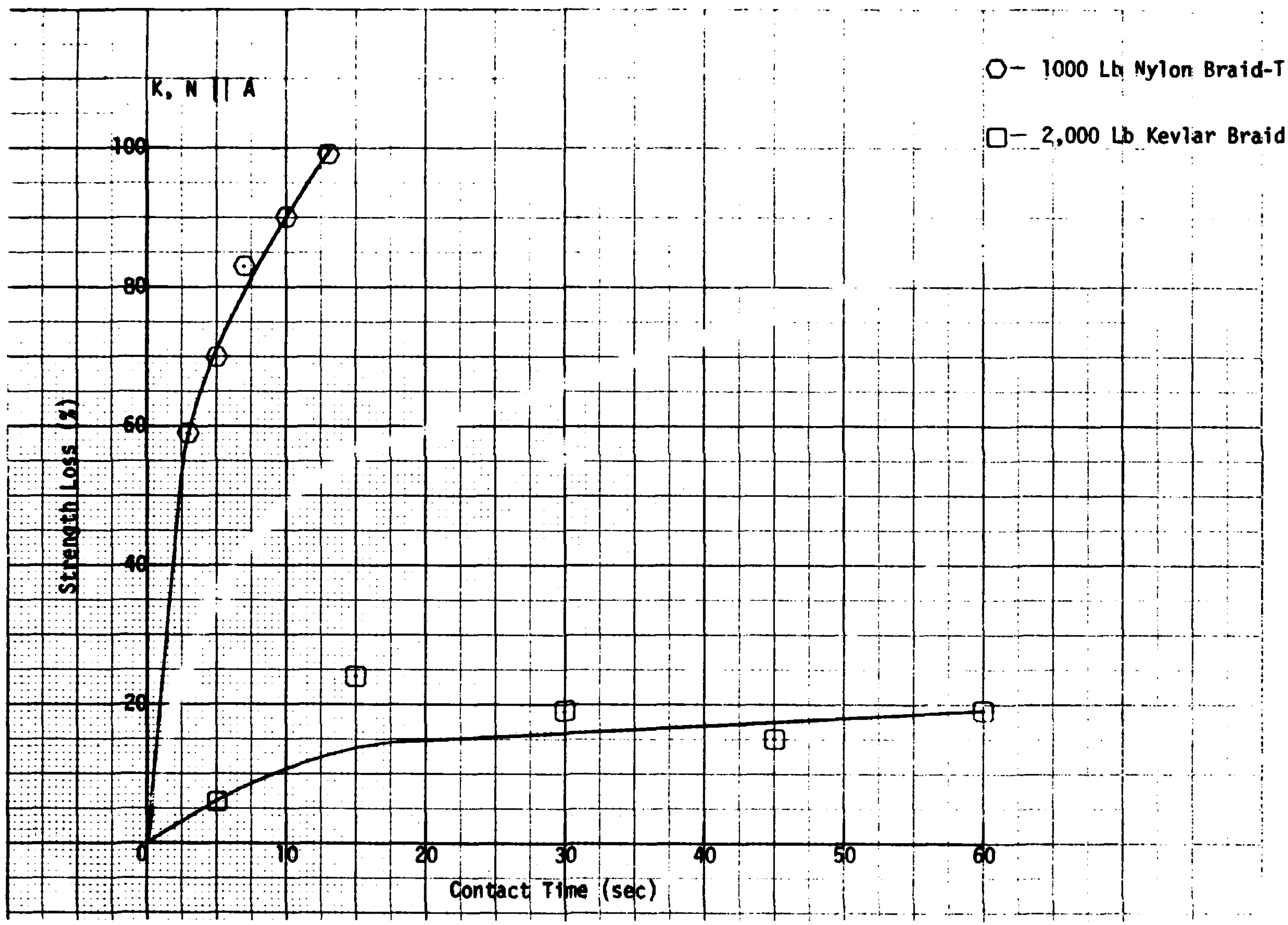


Figure 77. Strength Loss as a Function of Contact Time for Two Similar Braids Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at a Speed of 20 fps Using a Contact Force of 5 Lb

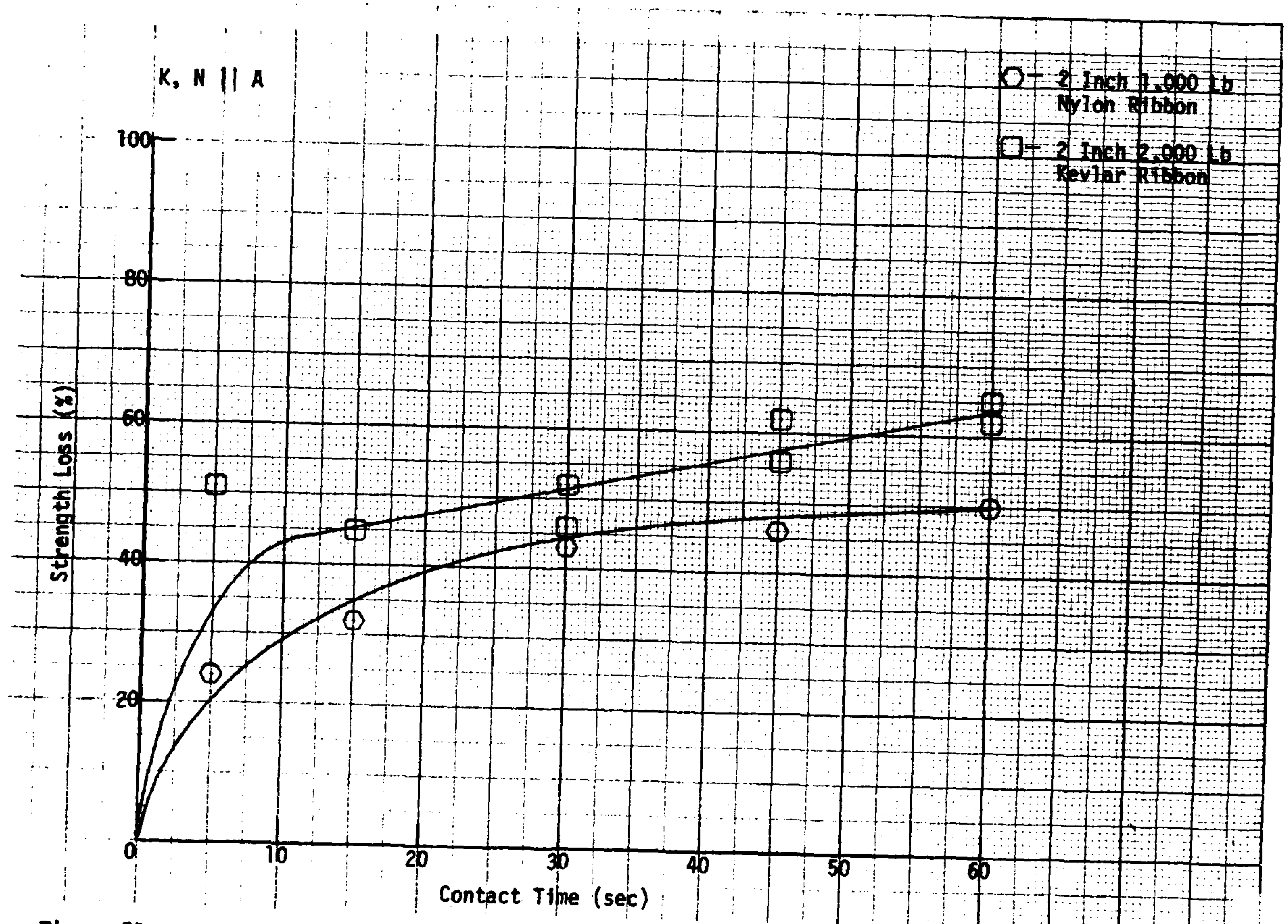


Figure 78. Strength Loss as a Function of Contact Time for Two Similar Ribbons Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at a Contact Speed of 20 fps Using a Contact Force of 1 Lb

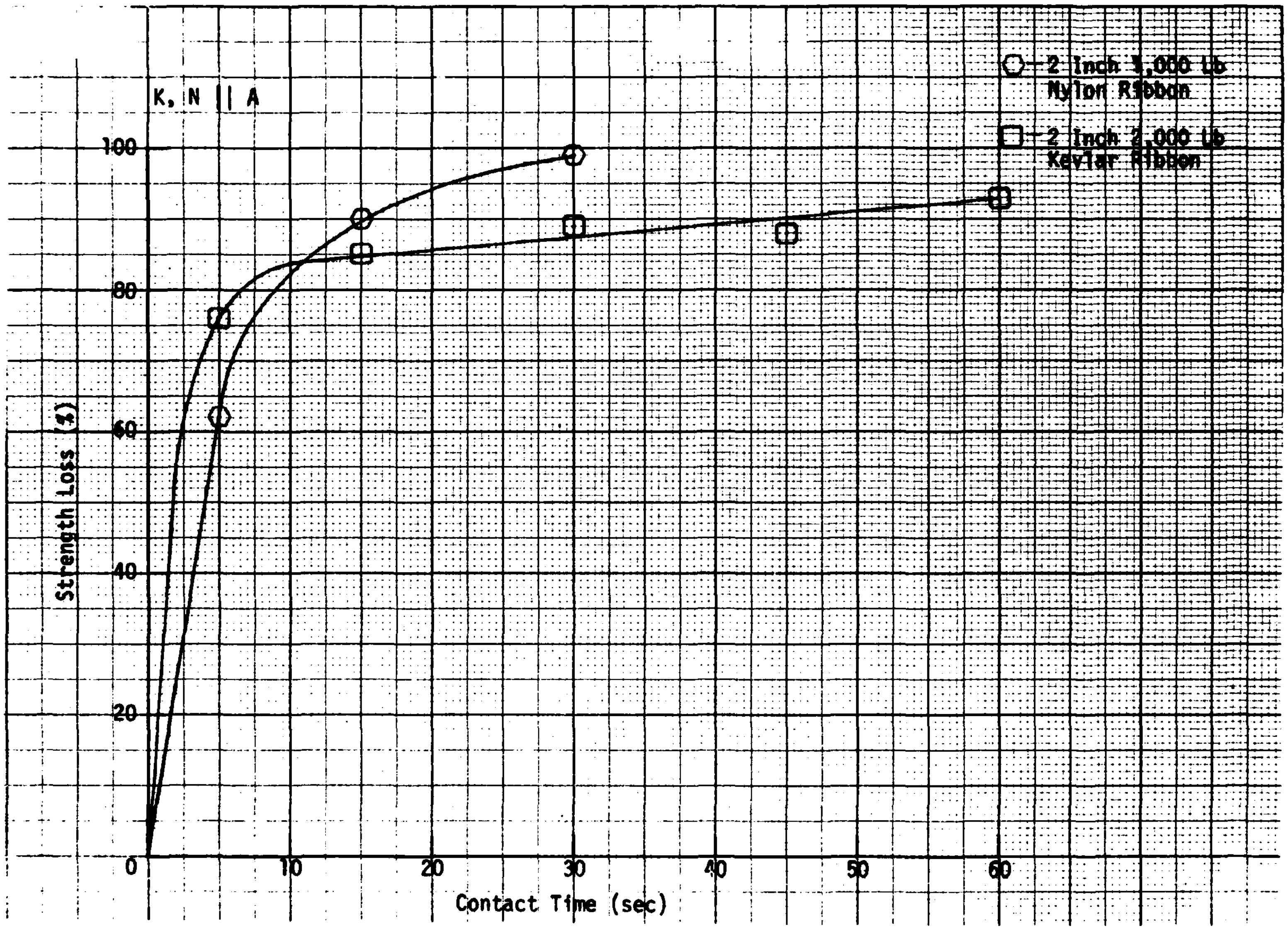


Figure 79. Strength Loss as a Function of Contact Time for Two Similar Ribbons Abraded in the Kevlar (Nylon) on Abrasive Parallel Configuration at a Contact Speed of 120 fps Using a Contact Force of 1 Lb

ribbons sustained high strength losses in short times and the nylon ribbon showed slightly superior abrasion resistance. At longer contact times, the Kevlar ribbon demonstrated slightly better abrasion resistance, possibly due to its thermal stability. The abrasion resistance of both ribbons was similar at both speeds. Indications from this testing again were that Kevlar's performance improved relative to that of nylon as test speed was increased.

The 700 lb Kevlar ribbon was abraded in the Kevlar on abrasive perpendicular configuration at speeds of 20, 40 and 80 fps using a contact force of 1 lb. No scorching was evident in any of the specimens tested. In previous testing at these conditions, the abrasion resistance of the 460 lb nylon ribbon was superior to all other ribbons. This was attributed to its construction which allowed for filling yarn abrasion under high specimen tension due to increased filling yarn crimp. Inspection of the abraded 700 lb ribbons showed that it too exhibited abrasion in the filling yarns. Figures 80, 81 and 82 compare the results of abrasion of these two ribbons. The abrasion resistance of these ribbons was similar at short contact times. At longer contact times, the Kevlar ribbon exibited slightly better abrasion resistance. The difference in abrasion resistance between the two ribbons was consistent for all three test speeds, which was somewhat unexpected. The main conclusion drawn from this data was that the previous assumption that of the poor abrasion resistance of the lightweight Kevlar ribbons had a lower resistance to abrasion than the nylon ribbons was due to constructional differences, was correct. When the structural geometries were similar, the differences between nylon and Kevlar were either small, or the Kevlar material was significantly better than the nylon.

D. Summary

This series of tests served to reinforce several conclusions that were drawn from previous testing. The first of these was the conclusion that on the basis of material properties, excluding constructional effects, the abrasion resistance of Kevlar was at least equal to that of nylon at low speeds and superior to it at higher speeds and longer times. The poor performance of some Kevlar structures when compared with nylon was proven to be due to constructional effects. The indications were generally in favor of Kevlar's performance at high speeds which was previously assumed to be due to its superior thermal stability and higher melting temperature. The abrasion of these materials against themselves was shown previously to be dominated by thermal effects in most cases. The abrasion resistance of nylon under those conditions was poor due to its low melting temperature. Abrasion of these materials against a common surface was less dominated by obvious thermal effects and the abrasion resistance of nylon was found to be improved, relative to Kevlar, at low speeds. The data generated during the testing presented here showed conclusively that the high speed abrasion resistance of Kevlar was not consistent with its reputation for poor abrasion resistance.

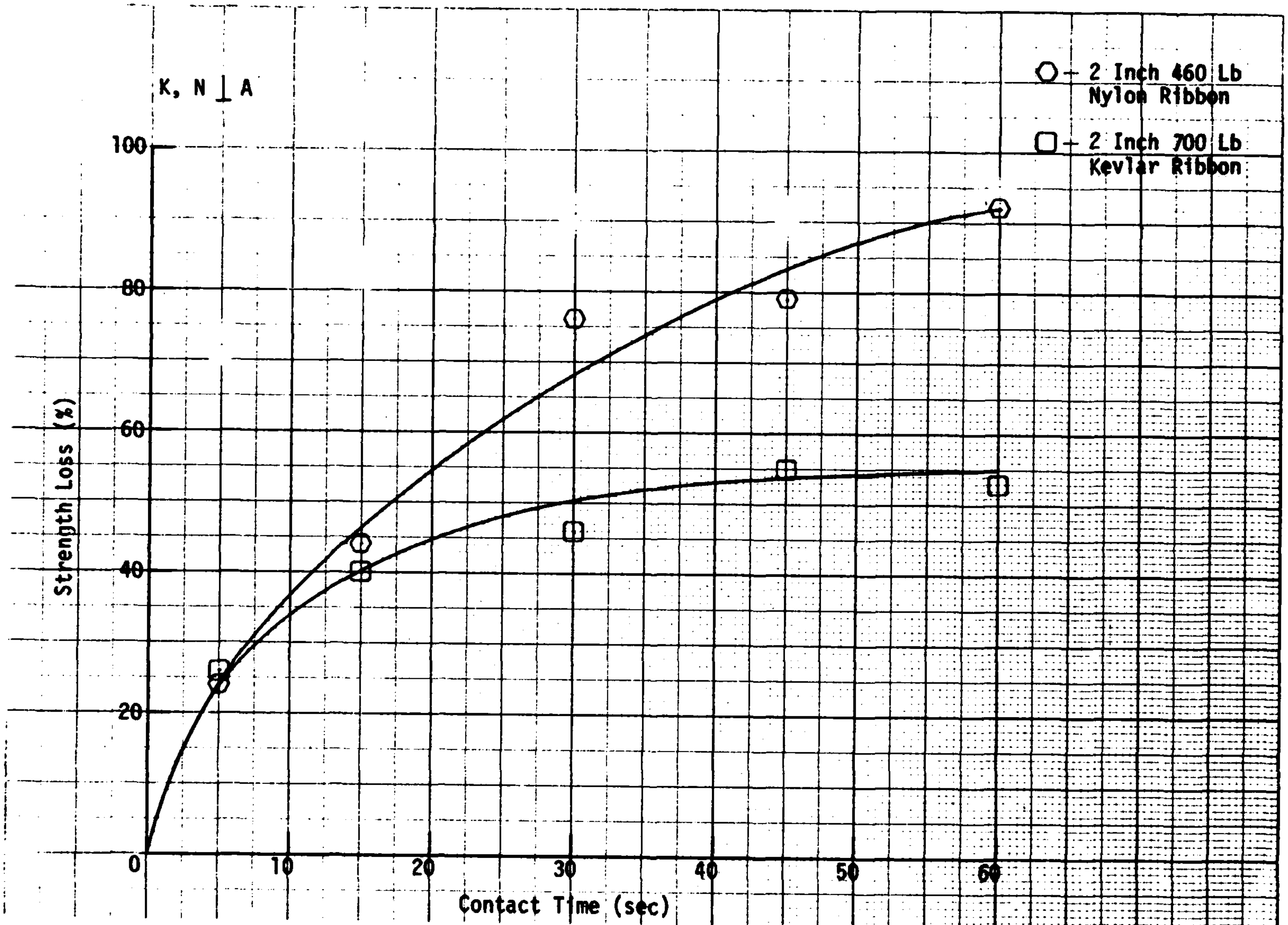


Figure 80. Strength Loss as a Function of Contact Time for Two Similar Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at a Speed of 20 fps Using a Contact Force of 1 Lb

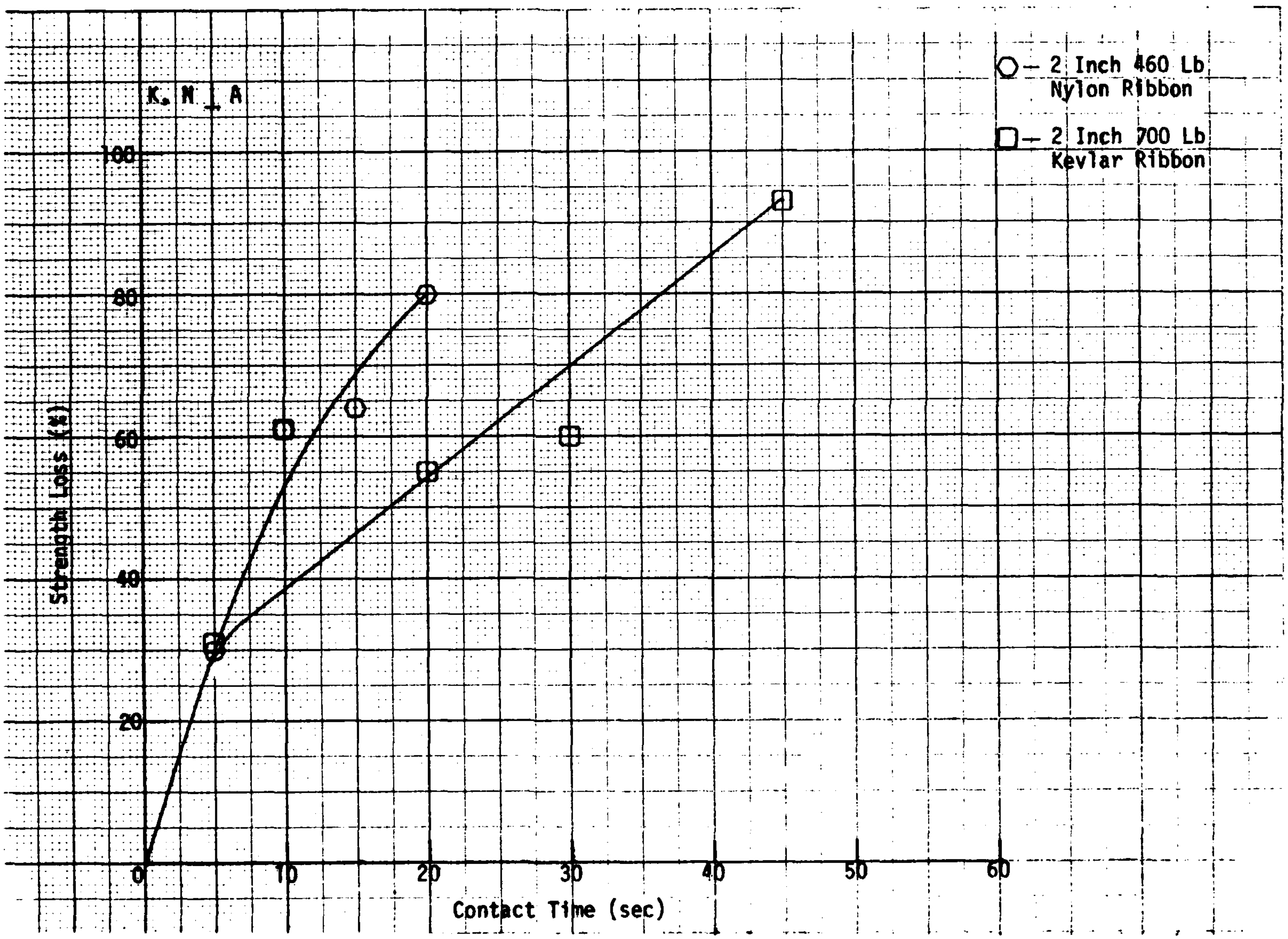


Figure 81. Strength Loss as a Function of Contact Time for Two Similar Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at a Speed of 40 fps Using a Contact Force of 1 Lb

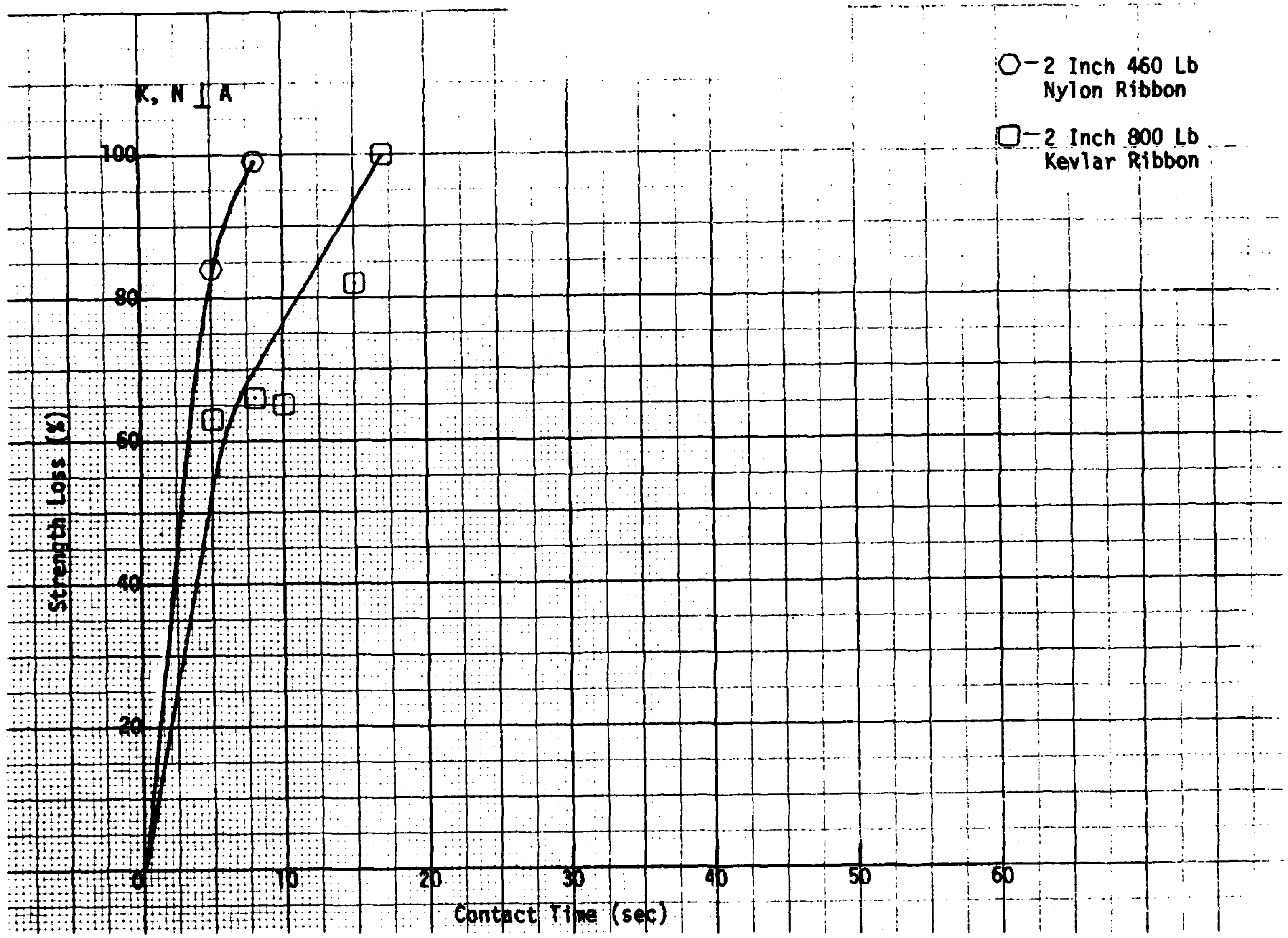


Figure 82. Strength Loss as a Function of Contact Time for Two Similar Ribbons Abraded in the Kevlar (Nylon) on Abrasive Perpendicular Configuration at a Speed of 80 fps Using a Contact Force of 1 Lb

SECTION XII

SUMMARY

A. Strength Loss Mechanisms

There were three mechanisms for strength loss found in this test program. These were, fiber breakage, thermal degradation and piling. The piling phenomenon was discovered early in the testing of the 6,000 lb Kevlar webbing and discussed in a previous section. This effect was seen as an opening or fuzzing of the yarns with loops of fibers protruding from the unabraded (upper) surface of the abraded specimen opposite the abraded area. It was believed to be due to compression of the yarns caused by cyclic impacting of the fabric knuckles. This theory was strengthened by the fact that increasing specimen tension delayed or eliminated this mechanism. The strength loss resulted from a length differential between fibers which caused poor distribution of tension among the fibers. Strength losses related to this mechanism were quite high. Very little was understood about this phenomenon and it did not appear to be controllable by or relatable to the parameters of the testing which were being varied. Because of this, and the fact that strength losses attributed to it were significant in relation to the total strength loss for the specimen, it was decided to avoid this in all testing. This was done by decreasing the length of contact between the abrading and abraded specimen. Investigation of this phenomenon could have been quite interesting, but was not possible within the scope of this program.

Thermal effects turned out to be an extremely important mechanism for strength loss in this testing. In some of the testing, strength losses were attributed exclusively to thermal degradation. Very little was known about the temperatures of the specimens in this testing. Investigation of this was also not possible within the scope of this project. Indications were, however, that specimen temperatures were quite high in many cases. Scorching, glazing and melting were evidence of this. Nylon melts at approximately 480°F (250°C). Temperatures in this range were obviously present in the testing of nylon on nylon where melting was extensive. Strength losses in this testing were found only in specimens which exhibited melting. In the nylon on abrasive testing, melting was observed in many of the test conditions. Testing at the milder conditions did sometimes result in abrasion without obvious melting. Under these conditions, however, there must have been some heating of the sample due to friction which may have resulted in some change in the mechanical properties of the material. Nylon typically loses 50% of its tensile strength at a temperature of 350°F in dry air. This change in physical properties must certainly have had some adverse effect on the abrasion resistance of the nylon.

Kevlar decomposes via oxidation at a temperature of 930°F (500°C) in dry air. Evidence of specimen temperatures in this range was obvious in many tests conducted in the Kevlar on Kevlar test configuration. Oxidation (or scorching) was characterized by varying degrees of specimen browning from a slight tinting on the peaks of the fabric knuckles to a complete blackening of the entire surface to the point where a brown tint was noticeable on the opposite (unabraded) side of the material. Oxidation of Kevlar occurs before melting under standard conditions at elevated temperatures. We have been told that Kevlar would melt, if conditions permitted it, at about 950°F (510°C), and that application of pressure could reduce this temperature to perhaps 350°C. In a few

harsh test conditions, a glazing and bonding of fibers resembling a melt was observed in the test samples. This also occurred with varying degrees of browning. Microscopic inspection of a typical scorched specimen revealed that the scorched fibers may or may not have been intact, retained essentially none of their original strength and were not bonded together. In specimens which displayed evidence of melting, fibers were bonded together whether they were scorched or not. In the Kevlar on abrasive testing, scorching was only evident at a few of the test conditions. Specimen heating, however, could still have affected the abrasion resistance of the Kevlar.

Fiber breakage was evident in all of the Kevlar abrasion and most of the nylon on abrasive testing. Fiber breakage was evident in scorched and unscorched Kevlar specimens. In general, nylon specimens sustained filament failure without melting only at mild conditions (low speed and contact force). Even at the mild conditions, specimen heating must have affected filament strength adversely. Comparison between Kevlar and nylon abraded under conditions which were totally devoid of thermal effects was therefore impossible. Pure fiber and filament failure was therefore found to be a minor contributor to strength loss for nylon and believed to be only really significant in the Kevlar on abrasive testing.

B. Kevlar/Nylon Comparison

1. Webbings

Comparison of results for all abrasion configurations showed superior abrasion resistance of Kevlar webbings over nylon. The 9,000 lb Kevlar webbing and the 6,000 lb nylon webbing were similar but not identical in weight, thickness and construction. The 6,000 lb Kevlar webbing was significantly different from the nylon webbing which resulted in differences in abrasion resistance which was apparently inherent in the structure. However, only in the abrasion on abrasive paper, where severe nylon melting was avoided, was the nylon webbing similar to the 6,000 lb Kevlar webbing in abrasion. In all testing of Kevlar on Kevlar (nylon on nylon) heat effects resulted in enormous differences between the abrasion resistance of the Kevlar and nylon webbings. The 9,000 lb Kevlar webbing, however, was substantially better than the nylon in all areas of testing. The effects of both contact force and speed on strength loss were much greater for the nylon webbing than Kevlar because of nylon's sensitivity to melting. Data scatter was greater for the nylon materials abraded in the melt situations than for non-melt situations or for any type of Kevlar abrasion. The effect of higher specimen tension seemed to improve the abrasion resistance of the 6,000 lb Kevlar webbing where it did not significantly affect the abrasion resistance of the nylon webbing. Comparisons between identical weaves of Kevlar and nylon showed conclusively that Kevlar's performance was superior to that of nylon in the webbing form when the two were abraded at a high speed against a common surface. All indications from this testing were that replacement of nylon suspension line materials with Kevlar on a rated strength basis certainly would not result in any decrease in performance and could result in improved abrasion resistance of the entire structure under many conditions.

2. Braids

A comparison of abrasion resistance between the braids was difficult in many cases because of the small contact areas, sensitivity to load and speed conditions and therefore the use of different loading conditions at different speeds for some test configurations. Substantial differences in size and

structure between the two braids also complicated the comparison. The nylon braid was almost twice the size of the Kevlar braid and yarns in the Kevlar braid were oriented more parallel to the longitudinal axis of the braid than they were for the nylon braid. The nylon braid dimension tended to lend an advantage to that braid in all testing. The yarn orientation gave an advantage to the Kevlar braid in parallel testing and the nylon braid in perpendicular testing. The Kevlar braid, therefore, exhibited significantly better abrasion resistance than the nylon braid in all parallel abrasion. Even in the only non-melt parallel abrasion for nylon (nylon on abrasive at 20 fps), the Kevlar braid performed substantially better than the nylon. In the perpendicular abrasion, abrasion resistance of the two braids was much more similar. In this testing, the nylon braid performed better than the Kevlar braid at low speeds. In the Kevlar perpendicular testing at 20 fps the nylon braid performed better than the Kevlar. However, the Kevlar braid was abraded at speeds of 80 and 120 fps which was impossible to do with the nylon braid. Testing of the nylon braid at 40 fps with a 5 lb contact force was also impossible, but not with the Kevlar braid. In the perpendicular on abrasive abrasion, tests were conducted with both braids at identical conditions. Here, the nylon braid did perform better than the Kevlar braid at all three speeds used. However, these differences in abrasion resistance became smaller as the test speed was increased and at 80 fps their performance was very similar. In general again, the effects of speed and load were much greater for nylon than Kevlar even where thermal effects were minimized. Data scatter for both braids was higher than what was found in the webbing testing. However, data scatter was a problem in some of the nylon braid tests performed in melt situations. The effect of tension was only superficially investigated but it did not appear to be too great. Again, comparisons between braids of identical construction made from Kevlar and nylon showed conclusively that Kevlar's abrasion resistance was superior to nylon when the two were abraded against a common surface in the parallel configuration. Indications from this testing were that replacement of nylon braids with Kevlar in decelerator systems, on the basis of rated strength, would not seriously affect the performance of the system. In fact, certain advantages in the area of abrasion resistance and longevity could be gained by such a change. It would appear that sacrificing some of the bulk and weight savings, realized by the replacement of nylon with Kevlar, for increased abrasion resistance, by using a slightly stronger Kevlar braid, would dispel any doubts about braid performance in these systems.

3. Ribbons and Lightweight Webbing

Constructional differences between the five ribbons considered were enough to make comparisons between them dubious. This was evidenced by the fact that the 460 lb nylon ribbon performed better than 1,000 lb nylon ribbon in perpendicular abrasion on abrasive paper. These materials were only tested on abrasive paper using the minimum contact force and low speeds. This therefore minimized thermal effects. In general, the nylon materials exhibited better abrasion resistance than the Kevlar materials when compared on the basis of strength. The constructional differences believed to be at least partially responsible for the differences in abrasion resistance were discussed extensively in previous sections under Kevlar/Nylon Comparisons. Basically, the differences were in the use of a plain weave for the Kevlar materials and a twill construction for nylon which resulted in a high contact area and good yarn orientation. In the perpendicular configuration, both 1,000 lb ribbons performed similarly, whereas in the parallel configuration the difference was enormously in favor of the nylon ribbon. Comparison between the 480 lb Kevlar

and 460 lb nylon ribbons was not possible except where the Kevlar ribbon could be tested at 20 fps in the parallel configuration. The 480 lb Kevlar ribbon was extremely sleazy and suffered from yarn skewing. Even the 1-3/4 inch 4,000 lb Kevlar webbing was damaged more than the 1,000 lb nylon ribbon in parallel abrasion and more than the 460 lb nylon ribbon in perpendicular abrasion. In both of these abrasion configurations, the nylon material showed a greater effect of speed on the abrasion than the Kevlar. Testing at 80 fps yielded similar or superior abrasion resistance of the 4,000 lb Kevlar webbing over the nylon ribbons. However, in all of this testing, these materials sustained high strength losses at mild test conditions. Perhaps the excellent performance of the nylon relative to Kevlar was due in part to the minimization of heat generation with the use of low speeds and contact pressures. This was indicated by the lack of obvious thermal effects and the similarities in abrasion resistance of identical constructions of nylon and Kevlar seen previously. Replacement, on the basis of rated strength, of nylon ribbons with Kevlar ribbons in parachutes could result in reduced longevity from low speed contact of the ribbons with a rough surface such as concrete. In the case of high speed contact, the difference would probably not be detectable. In the case of rubbing between ribbons during deployment, a definite statement could not be made due to a lack of data for Kevlar on Kevlar (nylon on nylon) abrasion. The ratios of strength to weight for these lightweight structures were quite different from Kevlar to nylon. If good abrasion resistance were a critical requirement, the use of a less efficient twill construction for the Kevlar ribbons could result in substantially improved abrasion resistance with a small decrease in the strength to weight ratio for the structure.

C. General

The purpose of this program was to evaluate, and compare with nylon, the high speed abrasion resistance of several different Kevlar constructions in various rubbing configurations through a range of speeds and conditions in order to simulate the use of a decelerator system. The replacement of nylon with Kevlar in these systems represented a substantial savings in weight and bulk. However, Kevlar has had a reputation for poor abrasion resistance which had left serious doubts about its use in these systems. The results of this program showed that the reputation of Kevlar was unwarranted. In many instances, the performance of the Kevlar materials was far superior to that of the nylon materials. The abrasion resistance referred to here was not limited to fiber breakage but was inclusive of thermal effects (scorching, melting, bonding and reduction in fiber strength at elevated temperatures). In many cases, the thermal effects appeared to be the main strength loss mechanism. In high speed rubbing, such as in this testing, heat generation was inevitable.

Nylon's low melting point made it much more sensitive to thermal effects than Kevlar. Since heat generation was directly related to contact speed and force, nylon was therefore found to be much more sensitive to test speeds and forces. In addition to the large effects of speed and force on abrasion of nylon, the onset of melting was very sensitive to minute changes in test conditions and the rate of strength loss after the onset of melting was very high. All of this resulted in uncontrollable testing of nylon and high variability of results.

Kevlar, on the other hand, exhibited much smaller speed and force effects, much lower variability and better reproducibility of data than nylon. Abrasion at conditions of high heat generation where thermal effects

were a primary strength loss mechanism showed that Kevlar was far superior to nylon, regardless of constructional effects, due to Kevlar's high degradation temperature and good thermal stability. Even at conditions of abrasion where thermal effects were minimal the performance of the Kevlar materials was often equal or superior to the abrasion resistance of the nylon materials.

The design of these Kevlar materials on the basis of a maximum strength to weight ratio resulted in many of these structures being less than optimum for good abrasion resistance. Even in these structures, however, the abrasion resistance of Kevlar was seldom poorer than that of nylon. Replacement of nylon with Kevlar on the basis of rated strength could be done safely with webbings and braids without significantly decreasing abrasion resistance.

This program showed that the lightweight nylon materials exhibited superior abrasion resistance to that of the lightweight Kevlar materials compared on the basis of rated strength, inclusive of apparently substantial constructional differences and effects. However, the abrasion resistance of all of these materials was so poor that, most likely, interchanging of these structures would not have any significant effect on the abrasion resistance of the system. Furthermore, a redesign of some of these materials using a construction which had inherently good abrasion resistance could dispel any doubts concerning the interchanging of these materials with only a minor sacrifice of the bulk and weight savings gained by this switch.

Interest in this program stemmed from a desire to compare the abrasion resistance of Kevlar and nylon on the basis of rated strength. As has been mentioned previously, constructional effects often made a comparison on this basis difficult. A true comparison of abrasion resistance of the two materials was made between identical structures which showed that the abrasion resistance of Kevlar as a material was generally equal to or better than nylon. Identical structures of Kevlar and nylon resulted in a much higher strength for the Kevlar structure than the nylon. Replacement of nylon with Kevlar on this basis would eliminate the bulk and weight savings and only serve to strengthen the system for the purpose of equaling or surpassing the abrasion resistance of the nylon system. It is understood that comparison of abrasion resistance on the basis of identical structures is of little importance to the parachute designer. However, it is the only viable way to compare the inherent abrasion resistance of two materials without the contribution of constructional effects. Nylon was generally accepted as one of the most abrasion resistant textile fibers available. The mere fact that Kevlar was abraded under conditions similar to those used for nylon, with only a few instances where Kevlar was significantly poorer than nylon, demonstrated that Kevlar did not have poor abrasion resistance. The fact that, in the face of inherently poor abrasion resistant structures, Kevlar's performance was more often equal or superior to that of nylon further strengthened this conclusion. Finally, the substantially superior abrasion resistance of Kevlar over nylon in comparisons where constructional effects were minimized even further strengthened the conclusion that Kevlar, as a material, did not have poor abrasion resistance when abraded under high speed conditions.

SECTION XIII

CONCLUSIONS

Kevlar materials were generally found to lose less strength as a result of high speed abrasion than their nylon counterparts. Failure of nylon materials was dependent primarily upon nylon's extreme sensitivity to the elevated temperatures which are the result of high speed rubbing. Kevlar's strength is reduced only about 25% at the temperature which melts nylon (460°F) and, for exposures of very short duration, obvious thermal damage in the form of melting and charring only occurs at estimated temperatures of about 900°F. As a result, Kevlar materials were capable of maintaining a significant fraction of their initial strength under abrasion conditions which caused essentially immediate failure in their nylon counterparts.

Rate of strength loss due to abrasion in nylon materials, and to a lesser extent in Kevlar, is strongly affected by the speed of rubbing and the normal force between the specimen and the rubbing surface. This is also believed to be related to the influence of these variables on the temperature rise in the specimen, though no objective measurements of temperature were made.

The one case where Kevlar materials did not stand up as well as their nylon counterparts was in the lightweight ribbons. In this case, the openness of the Kevlar constructions required the use of mild rubbing conditions, and seemed to make them particularly susceptible to abrasive damage which was not primarily related to thermal effects.

Kevlar materials may also exhibit strength losses resulting from a process which has been called piling, evidenced by the appearance of small loops of filament protruding from the side of the specimen opposite to the area being rubbed. This causes serious length unbalance in the load-bearing fibers, which can result in serious loss in structural strength. This phenomenon was observed but not studied in the present work. It occurs only under an appropriate combination of low specimen tension, construction, and rubbing or bending, and can be completely eliminated by increasing specimen tension. Piling has also been observed in nylon materials, but because of nylon's high extensibility it has a greatly reduced effect on structural strength.

Kevlar materials can withstand any high speed rubbing that may be encountered in decelerator systems deployment and operation better than their nylon counterparts, except when the Kevlar structures are lightweight and very loosely woven, or when a presently undefinable combination of conditions exist which result in the phenomenon called piling.

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